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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

APRIL 1955

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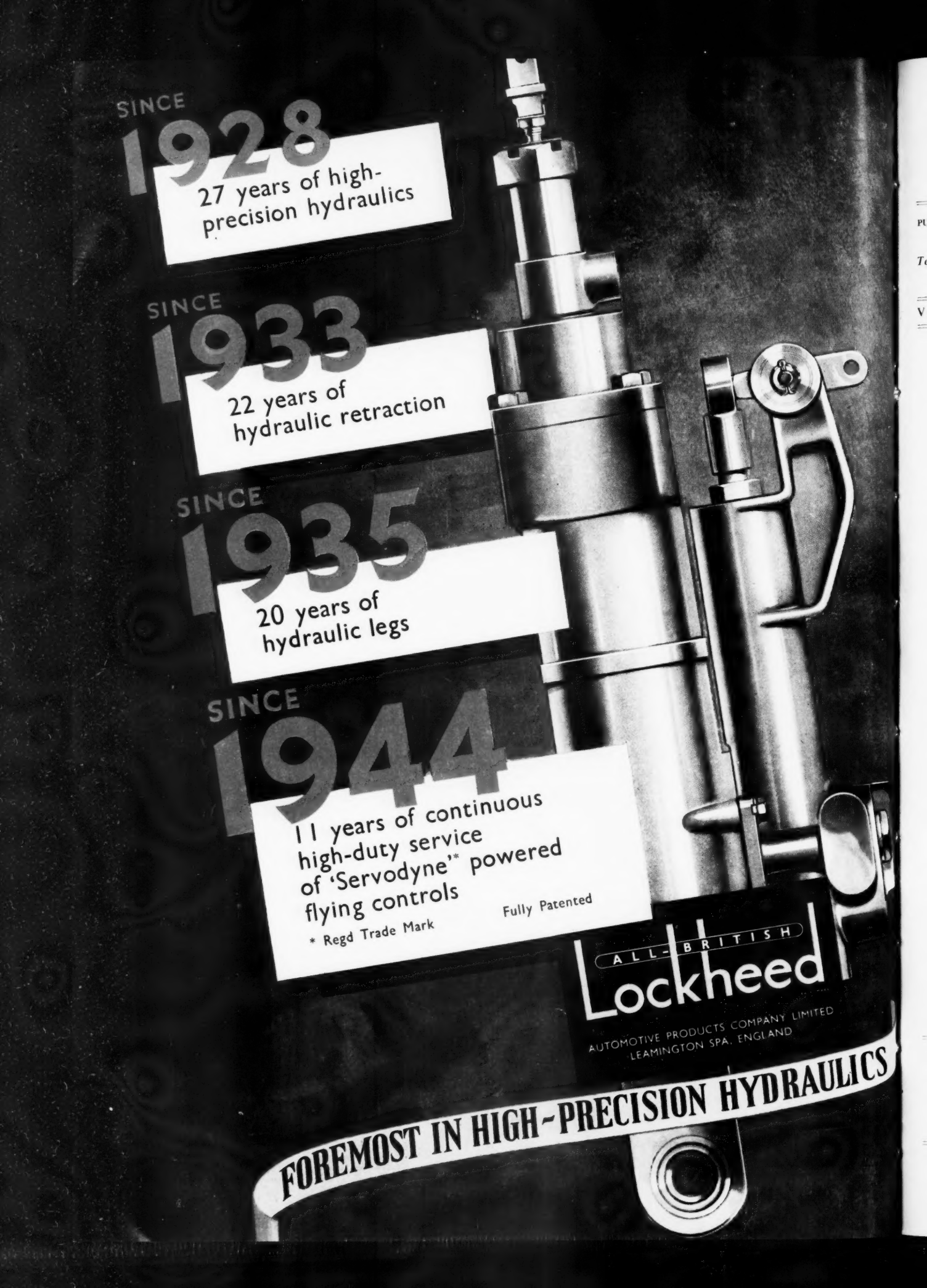
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All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Nominations of Candidates for Council

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained on application to the Secretary and should be returned by 10th April.

43rd Wilbur Wright Memorial Lecture

The 43rd Wilbur Wright Memorial Lecture will be held on Thursday 19th May 1955 at 6.0 p.m. at the Royal Institution, 21 Albemarle Street, W.1. Tea will be served at 5.30 p.m.

The subject of the lecture is "Flight Control" and the lecturer will be Dr. C. S. Draper, F.I.A.S., of Massachusetts Institute of Technology.

Awards to Members

Dr. L. Aitchison (*Fellow*) has been given the Insignia Award in Technology by the City and Guilds of London Institute, for his work in Metallurgy.

Mr. N. E. Rowe (*Fellow* and President-Elect) has been presented with a Diploma of Fellowship of the City and Guilds of London Institute.

Mr. Philip Wills (*Associate Fellow*) has been awarded the Lilienthal Medal for 1954, and also the Paul Tissandier Diploma by the Féderation Aéronautique Internationale.

Monsieur Jean Brocard (*Associate Fellow*) has been awarded the Medaille de l'Aéronautique.

Acknowledgments

The Council acknowledge with grateful thanks the receipt of several items of historical interest, presented by Erik Hildes-Heim of Fairfield, Connecticut. They include "The First Air Voyage in America" by Blanchard, "The Prehistory of Aviation" by Laufer and an engraving of Mademoiselle Godard's ascent at Copenhagen.

They also acknowledge with thanks a number of historic photographs presented by H. Cowley, *Companion*, and old reports from Dr. W. D. Douglas, *Fellow*.

Annual General Meeting, 5th May 1955

Notice is hereby given that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday 5th May at 5.30 p.m. in the offices of the Society, 4 Hamilton Place, London, W.1.

Agenda

1. To read the Notices convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheets and Income and Expenditure Accounts of the Royal Aeronautical Society and Aeronautical Trusts for the year ended 31st December 1954.
3. To receive the names of those elected to Council for the years 1955-58.
4. To announce the names of Fellows elected by the Council in accordance with By-Law 4.
5. To elect the Auditors for the year 1955.
6. Any other business.

By order of the Council
A. M. Ballantyne,
Secretary.

Note: In accordance with the By-Laws any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served after the meeting.

Easter Holidays

The Library and Offices of the Society will be closed from Thursday afternoon, 7th April until Tuesday morning, 12th April 1955.

Library

The Library of the Society will be closed on 1st, 2nd and 3rd June.

Associate Fellowship Examinations

The Associate Fellowship Examinations in the old and Revised Syllabus will be held in the offices of the Society on 1st, 2nd, 3rd June. Full particulars will be sent direct to all Candidates.

Graduates' and Students' Section

A visit to the Hawker Aircraft Co. Ltd. has been arranged on Saturday 21st May 1955. Members wishing to attend this visit should apply to the Hon. Visits Secretary, Mr. P. D. Stewart, 217 High Road, East Finchley, N.2. Applicants are asked to state their grade of membership of the Society.

Symposium on Aluminium in Shipbuilding

A Joint Symposium on the "Use and Welding of Aluminium in Shipbuilding" is to be held in London at the Institution of Naval Architects on 7th and 8th December 1955. An Organising Committee has been established, representing the Institute of Welding and the Institution of Naval Architects, the British Shipbuilding Research Association, the British Welding Research Association and the Aluminium Development Association.

The Secretary of the Symposium is Mr. G. Parsloe, Secretary of the Institute of Welding.

Associate Fellowship Examination Results—December 1954

The following candidates were successful in the Associate Fellowship Examination held in December 1954:—

Part I—London

B. G. Ambrose, Aerodynamics I.

L. F. M. de Swart, Applied Mathematics, Strength of Aircraft Materials and Theory of Structures I, Theory of Machines; D. J. W. Doswell, Aerodynamics I.

C. F. Forer, Applied Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Aircraft Materials and Theory of Structures, Theory of Machines.

Cadet F. M. A. Hines, Aerodynamics I, Theory of Prime Movers and Fuels; K. G. Hodson, Properties of Matter, Heat, Light and Sound, Aerodynamics I; J. E. Hughes, Theory of Machines.

P. G. King, Applied Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Aircraft Materials and Theory of Structures, Theory of Machines.

D. G. Martin, Applied Mathematics, Properties of Matter, Heat, Light and Sound, Strength of Aircraft Materials and Theory of Structures, Theory of Machines; A. J. Middleton, Strength of Aircraft Materials and Theory of Structures, Theory of Machines.

Cadet J. P. T. O'Mahony, Aerodynamics I, Theory of Prime Movers and Fuels.

A. P. Plunkett, Strength of Aircraft Materials and Theory of Structures I.

C. Russell, Strength of Aircraft Materials and Theory of Structures I.

Flt. Cadet J. N. Sawyer, Magnetism, Electricity, Electronics, Aerodynamics I, Theory of Prime Movers and Fuels; K. M. Smith, Properties of Matter, Heat, Light and Sound, Strength of Aircraft Materials and Theory of Structures I, Theory of Machines; Miss P. M. Smith, Strength of Aircraft Materials and Theory of Structures I.

S. M. Turner, Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.

P. A. Wilson, Aerodynamics I.

Part I—New Syllabus

J. B. Hooton, Aerodynamics.

Part II

V. Angre, Strength of Aircraft Materials and Theory of Structures II.

R. Boocock, Aerial Survey and Aerial Photography.

M. Chandra, Strength of Aircraft Materials and Theory of Structures II; J. Churchill, Strength of Aircraft Materials and Theory of Structures II; F/O. D. C. Crowther, Air Transport, Engineering Economics.

R. E. Dunford, Strength of Aircraft Materials and Theory of Structures II.

S. M. Humphry, Aircraft Design.

D. C. Kohli, Strength of Aircraft Materials and Theory of Structures II.

A. E. Moniz, Strength of Aircraft Materials and Theory of Structures II.

E. Owen, Aerodynamics II.

Sqdn. Ldr. R. F. Plucknett, Aircraft Materials.

J. L. Rudkin, Strength of Aircraft Materials and Theory of Structures II.

B. Singh, Strength of Aircraft Materials and Theory of Structures II.

D. Wilkinson, Aircraft Design; J. W. Wisdom, Engine Design.

Part I—Abroad

K. G. Balija (India), Theory of Machines.

L. A. F. Hill (Canada), Applied Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I.

Captain M. Jelinek (Israel), Magnetism, Electricity, Electronics, Aerodynamics I, Theory of Prime Movers and Fuels.

M. V. Karve (India), Aerodynamics I, Strength of Aircraft Materials, Theory of Structures I; C. S. Krishnamoorthi (India), Applied Mathematics; K. Kumar (India), Theory of Prime Movers and Fuels.

F. Minhas (Pakistan), Theory of Machines; K. R. Ananda Murthy (India), Strength of Aircraft Materials and Theory of Structures I.

T. L. Narasimhan (India), Strength of Aircraft Materials and Theory of Structures I, Theory of Prime Movers and Fuels.

T. S. Nagesha Rao (India), Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I; B. N. Vaman Rao (India), Strength of Aircraft Materials and Theory of Structures I; G. R. Venkata Rao (India), Aerodynamics I.

H. R. Satyanarayana (India), Theory of Machines; M. Shamarao (India), Aerodynamics I; K. S. Subrahmanyam (India), Strength of Aircraft Materials and Theory of Structures I, Theory of Machines.

Part II—Abroad

J. J. David (India), Aircraft Design.

K. R. Ananda Murthy (India), Aerodynamics II.

C. S. Parameswaran (India), Strength of Aircraft Materials and Theory of Structures II; R. Parthasarathy (India), Strength of Aircraft Materials and Theory of Structures II.

S. L. Relan (India), Engine Design; G. R. Venkata Rao (India), Strength of Aircraft Materials and Theory of Structures II.

News of Members

S. H. Andrews (*Associate Fellow*), formerly of the Research Department of D. Napier and Son, is now Head of Dynamic Test Department of the de Havilland Engine Company.

Lt.-Col. C. O. Blakemore (*Associate Fellow*) has taken up an appointment with the Ministry of Supply as a Technical Staff Officer I at the Fighting Vehicle Research and Development Establishment.

H. W. L. Calder (*Associate Fellow*) is now Chief Draughtsman of the de Havilland Aircraft Company, Hatfield.

Sir Harold Roxbee Cox (*Fellow*) has been appointed an Independent Member of the Council of the Air Registration Board in place of the late Sir Maurice Denny.

E. Dymond (*Associate Fellow*) who has been engaged in a technical capacity with various companies since leaving Sangamo Weston Ltd. is making an extended tour of the United States and Canada.

O. L. L. Fitzwilliams (*Associate Fellow*) has been appointed Chief Engineer of Westland Aircraft Limited.

Air Marshal Sir Victor Goddard (*Associate Fellow*) has been appointed Assistant (Air) to the Managing Director of Elliott Brothers (London) Ltd.

Major H. Hemming (*Fellow*) has recently been appointed Chief Liaison Officer to Burnley Aircraft Products Ltd.

C. G. Hollowell (*Associate*) has been appointed Publicity Manager in the Commercial Division of D. Napier and Son Ltd. in succession to the late Mr. A. V. Bellamy.

Dr. J. C. Hunsaker (*Honorary Fellow*) has been re-appointed Chairman of the National Advisory Committee for Aeronautics for a further five year period.

J. Glyn Jones (*Associate Fellow*) has left for Canada to take up an appointment as Aircraft Designer with A. V. Roe (Canada) Ltd.

Raymond B. Maloy (*Associate Fellow*) has been appointed Aircraft Engineering Advisor in the Civil Aeronautics Administration in Paris.

W. D. Murray (*Fellow*) has been appointed Engineering Manager of Westland Aircraft Ltd.

F. NIXON (*Fellow*) has been appointed Chief Quality Engineer of the Aero Division of Rolls-Royce Ltd.

P. E. Q. SHUNKER (*Associate Fellow*) has been appointed Chief Designer of Westland Aircraft Ltd.

W. U. SNELL (*Associate Fellow*) has been appointed Executive Assistant to Air Commodore F. R. Banks (*Fellow*), Director of The Bristol Aeroplane Company. Mr. Snell was formerly Chief Executive of the Engineering Department of the Company's Engine Division.

D. N. WALKER (*Associate Fellow*) has been appointed Chief Engineer to the Wilmot-Breeden Group of Companies.

G. R. WOOLL (*Associate*) formerly of Genaire Ltd. (Canada) has become Managing Director and member of the Board of the newly formed Company, Kaman Aircraft of Canada.

AIR COMMODORE W. R. WORSTALL (*Associate Fellow*) has been appointed Director of Air Engineering, Air Ministry. He was formerly Director of Maintenance and Supply, Royal Pakistan Air Force.

D. J. WRIGHT (*Associate Fellow*) has been appointed Chief Mechanical Research Engineer with Export Packing Services Ltd.

Diary

LONDON

14th **April**
MAIN LECTURE AT GLASGOW BRANCH.—Mixed Power in Modern Aircraft. M. J. Brennan. The Royal Technical College, Glasgow. 7.30 p.m.
GRADUATES' AND STUDENTS' SECTION.—Radio Aids for Navigation and Blind-landing. Captain F. Ormonroyd. 4 Hamilton Place, W.1. 7.30 p.m.

19th April
SECTION LECTURE.—Thermoelasticity. Professor W. S. Hemp. 4 Hamilton Place, W.1. 7 p.m.

21st April
MAIN LECTURE.—Aeronautical Research in Sweden. Bo.K. O. Lundberg. The Institution of Mechanical Engineers, 1 Birdcage Walk, S.W.1. 6 p.m. (Tea 5.30 p.m.)

26th April
SECTION LECTURE.—Aerial Systems for Aircraft. R. A. Burberry. 4 Hamilton Place, W. 1. 7 p.m.

30th April
GRADUATES' AND STUDENTS' SECTION.—Visit to Vickers-Armstrongs, Weybridge. 10.30 a.m.

3rd **May**
SECTION LECTURE.—Plastic Structures. G. C. Hulbert. 4 Hamilton Place, W.1. 7 p.m.

4th May
GRADUATES' AND STUDENTS' SECTION.—Technical Aspects of Supersonic Aircraft Design. E. J. Catchpole and W. J. Eggington. 4 Hamilton Place, W.1. 7.30 p.m.

19th May
THE 43RD WILBUR WRIGHT MEMORIAL LECTURE.—Flight Control. Dr. C. S. Draper. The Royal Institution, Albemarle Street, W.1. 6 p.m. (Tea 5.30 p.m.)

21st May
GRADUATES' AND STUDENTS' SECTION. — Visit to Hawker Aircraft Co. Ltd.

BRANCHES

11th **April**
Halton.—Films: "Measuring Craftsmanship," "British Adventure." "Cinemagazine No. 13." Branch Hut, R.A.F., Halton. 6.45 p.m.

13th April
Glasgow.—Annual General Meeting. St. Enoch Hotel, Glasgow. 7.30 p.m.
Preston.—Annual General Meeting and Film Show. R.A.F. Association, Preston. 7.30 p.m.

14th April
Glasgow.—Main Lecture.—Mixed Power in Modern Aircraft. M. J. Brennan. The Royal Technical College, Glasgow. 7.30 p.m.

19th April
Belfast.—Annual General Meeting. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

20th April
Coventry.—Annual General Meeting and Films. Wine Lodge, Coventry. 7.30 p.m.
Hatfield.—Discussion Evening. de Havilland Restaurant, Hatfield. 6.15 p.m.

21st April
Southampton.—Nuclear Power Plants. Institute of Education, University of Southampton. 7 p.m.
Yeovil.—Carrier Operations (Wyvern). Lt.-Cdr. C. E. Price. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

26th April (*transferred from 5th April*)
Boscombe Down.—The Light Fighter. W. E. W. Petter, C.B.E. N.A.A.F.I., A. and A.E.E., Boscombe Down. 5.30 p.m.

27th April
Gloucester.—Annual General Meeting and Film Show. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.

28th April
Yeovil.—Annual General Meeting. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

4th **May**
Luton.—Rubbers in Aircraft. Staff Canteen. D. Napier & Son Ltd., Luton Airport. 7.30 p.m.
Weybridge.—Annual General Meeting, Vickers-Armstrongs Limited, Weybridge. 6 p.m.

9th May
Halton.—The History of Parachuting and Ejection Seats. A./A. R. D. Trender (Junior Member). Branch Hut, R.A.F., Halton. 6.45 p.m.

11th May
Chester.—Annual General Meeting. The Grosvenor Hotel, Chester. 7.30 p.m.

12th May
Glasgow.—Aviation Fuels. C. F. Holloway. Royal Technical College, Glasgow. 7.30 p.m.

16th May
Halton.—Films: "The Nature of Plastics," "Plastics," "Cinemagazine No. 16," "Progress of Fighter Aircraft." Branch Hut, R.A.F., Halton. 6.45 p.m.

18th May
Hatfield.—Annual General Meeting. de Havilland Restaurant, Hatfield. 6.15 p.m.

23rd May
Halton.—Dynamic Heating (the heat barrier). Sqdn.-Ldr. P. C. Cleaver, O.B.E. Branch Hut, R.A.F., Halton. 6.45 p.m.

25th May
Halton.—Visit to High Duty Alloys, Slough, Bucks.

Elections

The following is a list of new members and transfers of membership of the Society: —

Associate Fellows

David Abir (*from Graduate*)
Derrick George Beavis (*from Graduate*)
Ronald Hall Cross (*from Graduate*)
Denys Dalby
John Wilson Drinkwater
George Forrest
Ian Alexander Butler Gaunt (*from Graduate*)
Hugh Arthur Goldsmith (*from Graduate*)
Victor George Aidan Hatcher
William Anthony Kevin Igoe
Charles Edgar Probert Jackson (*from Graduate*)
Herbert Turner Jessop
Kenneth Sumner Lawson (*from Graduate*)
Thomas McCloghry (*from Graduate*)
William Hall McKinlay
Anthony John Monk (*from Graduate*)
John Oliver Montanaro (*from Companion*)
Harold Edgar Parish (*ex Graduate*)
Aubrey John Russell Pegler
John Remfry
John Sandford
William Sowden-Jones (*from Graduate*)
Selden Booth Spangler
James Gottlieb Wenzel

Associates

Ernest Lomas Baines
Vishwa Nath Bhardwaj
Edgar Howard Brown
Edward James Burrell
Charles James Arthur Connolly
Walter George Haggar
Ronald James Harman
John William Higgins
Stanley Clifford Idle (*from Student*)
Marcus Llewellyn Bruss Jones (*from Graduate*)
Robert Arthur Powell (*from Student*)
George Denis Randall
Edward Lloyd Russell
Leslie Bartle Webber

Graduates

Hedley Vandelow Allen (*from Student*)
Russell Boocock
David Chapman
Geoffrey Montague Coiley (*from Student*)
Derek Charles Crowther (*from Student*)
Roy Leonard Dommett (*from Student*)
Robert Philip Francis (*from Student*)
John Frederick Gordon Hart (*from Student*)
Alexander William Edward Henham
Donald John Leech (*from Student*)
Bernard William Ludwig
Peter Beaumont Morice (*from Student*)
Phillip Nichols
Brian Stevens

Students

Brian Francis Baxter
Kailas Chidambaram
Victor Philip Cook
Frank Whewell Eyre
Henry Cyril Farley
Keith Ralph Hodge
Frank Ireland
John Henry Kallender
Clive Sampson Leyland
John Keith Lonsdale
Alexander Marr
Ernest Hunter Miller
Stanley Alexander Moon
Peter Henry Sheather
Anthony Chamberlain Thompson
Derek John Wilsden
John Stephen Wingrove
Ian Winterbottom

Companions

Paul Peter Heller
Reginald Charles LeBosquet
Peter Harry Molyneux

Income Tax

In response to enquiries from members with regard to a rebate on Income Tax for their subscriptions, the following is a copy of a letter received from the Principal Inspector of Taxes.

Ref: H.R.S.54/C.I. 4420/63.

14th August 1928.

Dear Sir,

Further to your interview with Mr. Stoneley at this office on the 19th July I am now in a position to inform you that the Board of Inland Revenue will not raise objection to the allowance as an expense for Income Tax purposes of annual subscriptions paid by members who are

(i) assessable under Schedule D of the Income Tax Acts in respect of professional or trading profits, subject to the decision of the Commissioners who make the assessment that such subscriptions are sufficiently closely related to the business carried on, or

(ii) assessable under Schedule E in those cases only in which continued membership of the Society is an essential condition of the terms of appointment.

Yours faithfully,
Signed GEO. WILCOCK,
Principal Inspector of Taxes.

Secretary,
Royal Aeronautical Society.

Journal Binding

Permanent Binding

The new prices for permanent binding of Journals are:

1954 Volume (including packing and postage)	18s. 6d.
1953 Volume (including packing and postage)	19s. 0d.
Previous Volumes (including packing and postage)	18s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

Changes of Address

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars: —

Name (in block letters).	New address (in block letters).
Grade of Membership.	Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

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The Second Mitchell Memorial Lecture

Some Problems and Prospects in Civil Air Transport

by

PETER G. MASEFIELD, M.A., F.R.Ae.S., F.I.A.S., M.Inst.T.

(Vice-President of the Royal Aeronautical Society and Chief Executive of British European Airways)

Introduction

Reginald J. Mitchell of Supermarines—a North Staffordshireman, like myself, and, in the words of Joe Smith, "a practical engineer possessed of an abundance of plain, straightforward common sense; a man of drive and genius"—will go down to history as among the most inspired of those who had the good fortune to live and work in Aviation's pioneering days. During the short span of his active designing and engineering life—for the 16 years between 1920 and 1936—he produced 24 different aircraft types, so brilliantly and affectionately discussed by the great Joe Smith in his foundation Mitchell Memorial Lecture in January 1954. Mitchell's aircraft included, in the civil transport field, the "Sea Eagle" of 1923, which opened air services to the Channel Islands, the unique "Air Yacht" of 1929 and the very advanced 75,000 lb., 174 ft. span, six-engined, 40-passenger commercial flying boat of 1930 (Fig. 1), the contract for which was unfortunately cancelled as an economy measure in January 1932 after work was well advanced. As C. G. Grey said at the time, "If this is the Government's idea of economy, then God help England." Mitchell's six-engined commercial boat, like the Spitfire after it, was years ahead of its time. But for the economic crisis of 1931, R. J. Mitchell's name might well have been as closely linked with the progress of Air Transport as it has since been with air warfare.

"R.J.'s" supreme work was, undoubtedly, the Spitfire designed in 1934, first flown in 1936, and one of the great aeroplanes of all time. Alongside it came the B.12/36 bomber, his last design, and, in 1935, also in advance of its time. But for its destruction by enemy bombing it might well have played a significant part at the end of the War as the Spitfire did at the start. One cannot avoid also the rumination of what might have been a civil transport evolution of this bomber (Fig. 2) and the impact it might have had on early post-war British Civil Air Transport. Cruising at 300 m.p.h. for an operating sector distance of 2,000 miles with 40 passengers it could have provided just the performance which would have held off the challenge of the DC-4 and early Constellation in 1946 and the following years.

In 1935, when I happened to be for a period Chairman of the Graduates' and Students' Section of the Royal Aeronautical Society, "R.J." came to one of the informal discussions on aeronautical subjects which we ran at that time. He was working then on both the Spitfire and the big bomber, while, in the World about us, the DC-2 was beginning to proclaim the new commercial gospel of stressed skin, flaps, variable pitch propellers and retractable undercarriages. Discussion turned on this transport challenge and what the United Kingdom could do to overtake the Americans. "R.J.", pulling at his pipe, remarked—and I noted it down at the time—

> "I have no doubt that the design and development of an air liner today is as complex as any task in the aeronautical field."

This observation by "R.J.", in the light of subsequent events, so penetrating in its foresight and so concise in its accuracy, serves as a text for this Second Mitchell Memorial Lecture, and my excuse for linking the name of the designer of the Spitfire with Air Transport's needs.

The Transport Operator's Dilemma

To an air transport operator the aeroplanes he uses are the tools of his trade. If he buys wisely and well he may prosper. If he judges ill, he will lose—and lose heavily. Fortunate is he if he finds a designer with the genius of a Mitchell to minister to his needs.

At the same time the air transport operator has two choices—either he can "play safe" and order aircraft which are already in production with a performance and economies known and measured. Or he can venture forward and decide upon a new design which promises a substantial advance for the future, depending on the manufacturer of his choice for success.

*Given before the Southampton Branch of the Royal Aeronautical Society on 24th November 1954.

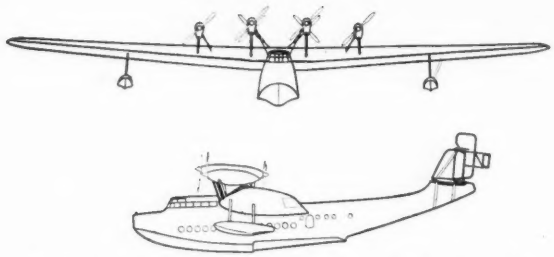


FIGURE 1. Supermarine Type 179. Six-engined commercial flying boat, 1931.

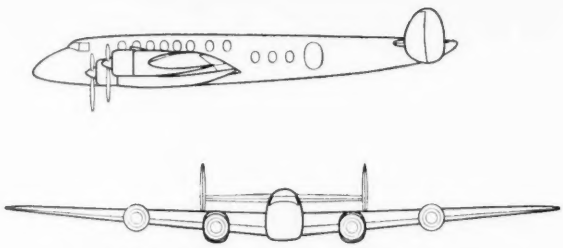


FIGURE 2. Supermarine Type 317 (B 12/36 bomber) (imaginative civil conversion).

In the one case—buying "off the peg"—the security of a known performance will be offset by the fact that the proved production aeroplane will, inevitably, be some eight years old in concept and thus, in some respects, obsolescent and less competitive than a new aeroplane straight from the drawing board. In the other case, the advantage of being a jump ahead of one's competitors is offset by inevitable teething troubles and, if the design has been ordered before a prototype has flown, there is a chance, not only of failure, but also of being left with no modern equipment to meet both competition and traffic's insistent demands.

"Nothing venture—nothing gain" and in the swiftly developing business of air transport the great successes come only from the great ventures.

Aircraft Lives

The life of a classic transport aeroplane design can now be set as nearer 15 years than the five over which it was traditionally "written off" before the War. And the 15 year period, incidentally, may well set a desirable life of structural integrity at around 50,000 flying hours without major rebuild.

Even so, with the swift march of the aeronautical sciences, no transport aeroplane is, as yet, likely to remain in front line service, on major routes, in its original form for more than about five or six years. Successive developments of airframe and engines may well extend the life of the basic design for a much longer time—such as the progression of the DC-4, through the DC-6 to the DC-7 in ten years. But, on present form, requirements for improved performance and improved economy, as well as for larger size, are likely to mean that a major airline will have to consider the introduction of a radically new design not less than once in every ten years; and that in each of its chief operating fields.

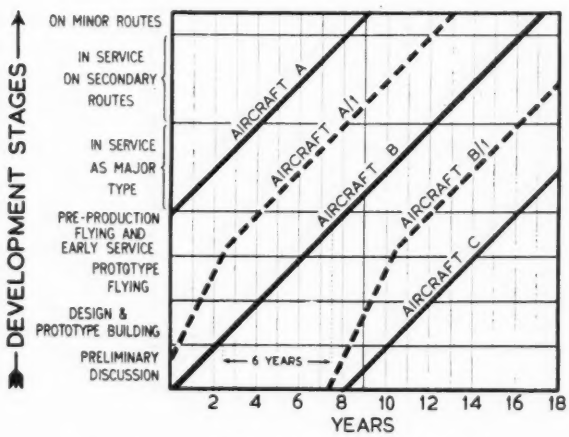


FIGURE 3. An airline's equipment time scale.

Why new?

On a few of the World's larger airlines falls the task of sparking a new design requirement. Once a clear specification of requirements has been evolved between operator and manufacturer other airlines usually join the bandwagon and, by the time the prototype is flying, the manufacturer's order book may be filling nicely.

What, then, are the reasons why impecunious airlines are prepared to lavish so much hard cash, and expensive technical development work, on that major headache—a radically new aeroplane?

First—the sheer needs of an expanding traffic. More capacity is needed to meet growing demands. The five-year-old "work-horse" is probably out of production, at least in its original form, and cannot be re-ordered. In any case, competition requires a faster aeroplane and the traffic growth demands something bigger if frequencies are to be kept within reasonable limits and airport congestion avoided. But most of all, rising prices and lower fares insist that better economy is produced—better economy by improved structures, better economy from increased size, but most of all, better economy from gains in engine performance—more power for less weight with lower fuel consumption and longer hours between overhaul. There will come a stage when none of these things can be gained in sufficient measure from the further development of a classic basic type. Then the new aeroplane is required.

Indeed, the heart of an aeroplane is its engines. Most new designs start around new power units, once the general size and configuration has been specified. And to the engine manufacturers must go a very large slice of the credit for the gains in speed and economy over the past 25 years.

An Airline's Equipment Time-Scale

Let us return, however, for a moment to the general time-scale in an airliner's life, which sets so insistently the requirements for re-equipment. The developing

situation may, perhaps, be set out as in Table I, the figures being generalised rather than specific.

Thus, in nine years the wheel may well come full circle (Fig. 3). The first type ("*A*") has been retired progressively from its ninth year of airline service—possibly sold to a lesser airline. The development ("*A*/1") of this first type has come into major service five years after the original design, from which it developed, began commercial duty and some five years after serious discussions upon the development aircraft began. The replacement type ("*B*") has progressed from first discussion into airline service (replacing "*A*/1" on major routes) in the course of nine years. Its development ("*B*/1") is on the stocks for service four years on while its replacement ("*C*") is just entering the requirements stage. At any one time, therefore, the airline has up to four types to contend with—the "old-stager" eking out its existence on secondary routes, the current major service aeroplane, its successor, which may be its development, and a brand new design still in its early stages. Whether the "nine-year-cycle" will expand or contract as the years go on remains to be seen. In all probability the cycle will extend as traffic growth tends to flatten, competition stabilises and designs become more complex. I forbear to say "and as technical advances slow up." In aeronautics there is no indication of that.

Airlines, and the manufacturers who supply them are thus, consciously or unconsciously, ceaselessly immersed in this cycle. The time scale may not be the same for all. But the fact that it exists in approximately this form for most major airlines, has a profound influence on all the others.

We have lived through two such complete cycles since R. J. Mitchell's day—upset, but not much interrupted, by the War. The first of these complete spirals, for instance, brought in and swept away the Empire "C Class" flying boats and their developments, the Hythes, Sandringhams and Solents. The second, in a rather different sphere, has seen the birth, maturity

TABLE I

GENERAL TIME-SCALE

	Major Type in Service	*Next Major Type*	*Future Development*
Year 1	*Aeroplane "A"* In first full year of service	*Aeroplane "A/1"* Development of "*A*" in design stage for full service in Year 5	*Aeroplane "B"* Radically new type—in preliminary discussion between operator and manufacturer for full service in Year 9
Year 2	*Aeroplane "A"* In second year of service	*Aeroplane "A/1"* Under construction in pre-production form	*Aeroplane "B"* Under discussion in various alternative forms
Year 3	*Aeroplane "A"* In third year of service	*Aeroplane "A/1"* Pre-production aircraft on service trials	*Aeroplane "B"* Design progressing on firm basis
Year 4	*Aeroplane "A"* In fourth year of service *Aeroplane "A/1"* Begins small scale operations	*Aeroplane "B"* First prototype nearing completion *Aeroplane "A/1"* Extensive training flying	*Aeroplane "B/1"* Development of "*B*"—contemplated, for full service in Year 13
Year 5	*Aeroplane "A/1"* In first full year of service *Aeroplane "A"* On secondary routes	*Aeroplane "B"* Prototype flying	*Aeroplane "B/1"* Contemplated
Year 6	*Aeroplane "A/1"* In second year of service	*Aeroplane "B"* Prototype on service trials and intensive flying	*Aeroplane "B/1"* Contemplated
Year 7	*Aeroplane "A/1"* In third year of service	*Aeroplane "B"* Pre-production aircraft on service trials and experimental services	*Aeroplane "B/1"* Contemplated
Year 8	*Aeroplane "A/1"* In fourth year of service *Aeroplane "B"* Begins small scale operations	*Aeroplane "B/1"* Under serious discussion *Aeroplane "B"* Intensive training flying	*Aeroplane "C"* Radically new type—contemplated
Year 9	*Aeroplane "B"* In first full year of service *Aeroplane "A/1"* On secondary routes *Aeroplane "A"* In course of retirement and relegation to minor routes	*Aeroplane "B/1"* In design stage to come into full service in Year 13	*Aeroplane "C"* In preliminary discussion between operator and manufacturer, to come into full service in Year 17

and the obsolescence on major trunk routes of such diverse types as the Viking, the DC-4 and the Constellation 049.

The airlines which buy their new aeroplanes "off the peg"—and they are the majority, however much they may prescribe individualistic interior details—do not concern us here in the context of "the Mitchell theme." All we may do is to bestow some slight envy on airlines whose competitive position and national responsibilities allow them to wait until they can buy a developed vehicle originally specified and "debugged" by someone else. The envy will not be all on one side, however, because the "reach-me-down" aeroplane possesses none of the satisfactions or contributions to progress which comes from the evolution of a tailor-made, and brand new, creation.

Prescription for Success

Every really successful civil transport aeroplane has been a result of a close, cordial and imaginative co-operation between operator and manufacturer. Indeed, one may say that it is the only recipe for success. The H.P.42 of 1931 came from close collaboration between Handley Page and Imperial Airways. The DC-2 and the DC-3 were inspired by T.W.A. and built by Douglas. The Empire Boat came from the collaboration of Imperial Airways and Short Bros. Ltd.; the Constellation was a product of T.W.A. and Lockheed; the Stratocruiser, of Pan American and Boeing; the Convair 240, from American Airlines and Consolidated Vultee; the Viscount, from B.E.A. and Vickers-Armstrongs. This collaboration between maker and user is becoming even more essential and detailed as the science progresses and the "learning curve" sweeps upwards. I go so far as to say that there can be no future successful transport aeroplane without it.

Basic Requirements

What then are the outline requirements which an airline must specify to start off a new design?

First—and basically—payload/range. The number of passengers and the sector distance over which they must be carried are the underlying and most important of the requirements.

Second—minimum acceptable normal cruising speed at specified power, height and weight.

Third—aerodrome performance; the length of runway from which the aeroplane must be capable of operating under specified temperature conditions together with, as an essential corollary, the maximum acceptable approach speed.

Fourth—special requirements. Such features as wing position, number and size of passenger and freight doors, number of toilets, absence of pneumatics, maximum height for hangar doors—and so forth.

Economic characteristics feature predominantly in an airline's initial statement of requirements but have to be expressed as derivatives of the controlling factors. Thus the economic performance of an aeroplane is implicit in the physical characteristics defined for it. Establish these and the economics, at any point on the time scale, will follow almost inevitably from the level of design skill applied. But it follows equally, that if the other requirements result in an uneconomic performance then the requirements will have to be altered to give a better result.

From the outline requirements evolve such vital matters as number and type of engines, fuselage dimensions and general configuration. These in their turn, govern all the aeroplane's operating characteristics.

The job of the operator is to say what he wants—clearly, concisely and in order of preference. Equally important, he must stick to it, basing his specific requirements on a close assessment of his needs and not, primarily, on hunches.

The job of the manufacturer is to try to offer the operator what he wants, ironing out inconsistencies and achieving the best engineering compromise between conflicting requirements. By the nature of the beast, the operator will try to insist on engineering impossibilities while the manufacturer will sometimes seek to persuade the operator that his commercial judgment is all wrong.

This is the stage at which a design can be made or marred. It calls for the closest possible collaboration and understanding between manufacturer and operator. Ideally there should be personalities on both sides who understand, and sympathise with, each others' problems and are in a position to take decisions without reference elsewhere.

For these reasons I am not in favour of design competitions. For major designs, at least, the trends are now—and, I believe, rightly—in the direction of a close collaboration between a major airline and one major manufacturer in the design and production of a new aeroplane. That collaboration must go on without interruption from first conception to full service. Given the right personalities the results can—in my opinion—be achieved in this way, both more quickly and with more certainty of success, than under any, more formal, contacts.

The process of collaboration must be detailed and must extend over years—through discussions, sketches, detailed drawings, mock-ups, prototypes, pre-production aircraft, service trials, training, introduction into service, the clearance of teething troubles and continuous service modifications. Sometimes it will strain relationships but in the long run, if it succeeds at all, it will cement a close bond of comradeship, the best guarantee of further success in future developments.

The process of years is, obviously, not a subject for detailed discussion here. But, what may be apposite is a more personal and specific expression of opinion on some of the major issues which come forward for settlement, in evolving, in the mid-1950s, a radically new aircraft design-requirement for medium range operations—an aeroplane which will see its major service between 1960 and 1970.

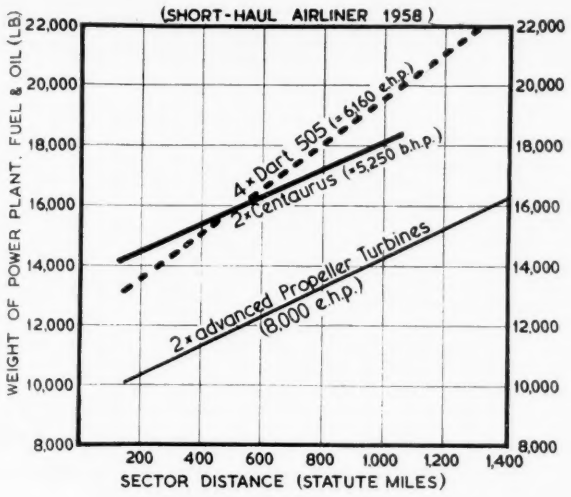


FIGURE 4. Power plant weights.

Power Plant Prospects

First, then—power plant. We in B.E.A. believe that there are overwhelming advantages in the advanced propeller-turbine engine, compared with any other available type of engine in the period under consideration. Analysis shows that such engines as the single-spool Napier Eland and the two-spool Rolls-Royce RB.109, are likely to be significantly ahead of any piston-engine, compound piston-engine, plain jet or by-pass engine, for the type of operation we have in mind.

From an airline's point of view, against a background of reliable maintenance characteristics, the most important factor is—for a given power—the total of the combined weights of power-plant, sector fuel, plus fuel allowances and reserves for the sector distances required.

Comparing, on this basis, four different types of engine for a typical short haul aeroplane we arrive at the following table:—

Power unit	*Combined take-off power*	*Cruising power*	*Total weight of power-plant, sector fuel and oil plus allowances and reserves for:* 400 *miles*	1,000 *miles*
Two Centaurus 661 (piston)	5,250 b.h.p.	2,600 b.h.p.	15,415 lb.	18,185 lb.
Four Dart 505 (turbo-prop)	6,160 e.h.p.	3,700 e.h.p.	15,120 lb.	19,670 lb.
Two developed turbo-props	8,000 e.h.p.	3,000 e.h.p.*	11,400 lb.	14,250 lb.

*Assumed limited for structural reasons in particular aircraft installation.

For the short and medium haul pattern considered the pure jet is not a starter. The advantage of the developed modern "turbo-prop" is apparent from the "brochure figures" (Fig. 4). Not only does it offer more power but gives it for less weight and less fuel consumption. The economy can be reflected directly in payload.

A major problem is, of course, how many engines?

Although powerful arguments can be made out in favour of the twin on grounds of simplicity and of ease of maintenance and lightness, the advantages of a four-engine layout, on commercial and psychological as well as operational grounds, seems to me to hold the day.

A modern, high performance, civil transport aeroplane must come out at a power loading of between six and nine lb. per e.h.p. for take-off to achieve a compromise between speed and economy. That means that a new 50,000 lb. aeroplane will require four power units of not less than 1,400 e.h.p. each for take-off—a 100,000 lb. aeroplane not less than twice this figure, preferably a good deal more. It means also that, with available engines, a new four-engine aeroplane is not, economically, possible between around 60,000 lb. with four 1,540 e.h.p. Dart 505s and around 90,000 lb. with four 3,000 e.h.p. Eland N.El.1s. Fortunately, traffic requirements demand bigger aeroplanes for the next decade.

The choice of engines will set not only the basic size and economy of the design, but also much of its reputation in airline service. It is indeed the element in the design which must determine, in major degree, what can be achieved by both designer and operator.

Fuselage Dimensions

The next point of importance to be determined by the airline is the standard of passenger accommodation.

Two—if not three—classes of airline seating have been evolved in the past two years—"Tourist" or "Standard" class, and "First class" or "Luxury" seating. The luxury standard is at present, invariably, four-abreast, two and two. "Standard class" is either four-abreast with a short pitch—of, say, 34 to 36 in.—(probably with non-adjustable seats), or five-abreast (three and two) with a wider pitch—of, say, 39 to 40 in. (semi-reclining). These conventions are not, however, inevitable. A luxury standard with, wider, five-abreast seating and a "standard class" with six-abreast seating (three and three) may be an aceptable alternative.

In the future, these seating standards can set the size of fuselage. To see how this may work out, examine desirable seat sizes. Reasonable figures may be set out as follows:

	Tourist (Standard)	*First Class (Luxury)*
Width of seat ...	18 in.	20 in.
Width of outer arms	2 in.	3 in.
Width of middle arms	3 in.	4 in.
Minimum width of gangway	18 in.	22 in.
Total Minimum Fuselage Width Inside		
Four-abreast (two and two)	108 in.* (9 ft. 0 in.)	122 in. (10 ft. 2 in.)
Five-abreast (three and two)	125 in. (10 ft. 5 in.)	146 in. (12 ft. 2 in.)
Six-abreast (three and three)	146 in. (12 ft. 2 in.)	

From this analysis (Fig. 5) one can see the interesting fact that a fuselage with an internal diameter of

*Determined also by "tumble home" of fuselage sides and position of floor relative to maximum diameter of fuselage.

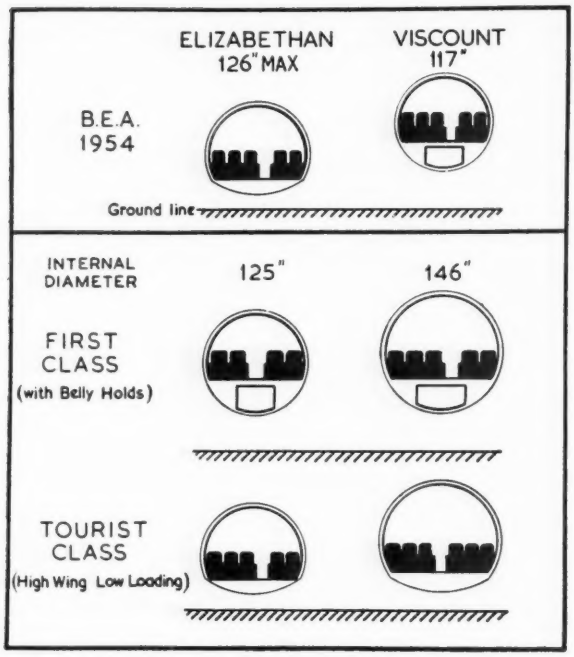


FIGURE 5. Fuselage widths.

125 in. (133 in. exterior diameter)—measured at the height of the arm rests with the floor substantially below the maximum diameter—would give adequate tourist five-abreast seating and better-than-adequate luxury, four-abreast, seating. A fuselage 21 in. wider, at 146 in. internally (156 in. externally) would offer adequate six-abreast tourist seating and five-abreast luxury seating—with the advantage of rather more headroom and better, under-floor, baggage capacity.

A fuselage of 125 in. internal diameter could have a capacity for 48 passengers (four-abreast) in first-class seating or 60 passengers (five-abreast) in tourist seating in 12 rows which, at 40 in. pitch, would occupy 40 ft. of cabin length. The wider fuselage of 146 internal diameter could have a capacity for 50 first-class passengers, five-abreast, or 60 tourist passengers, six-abreast, seated in ten rows—which, at the same 40 in. pitch, would occupy 33 ft. 4 in. of cabin length. Thus, the additional weight of the large diameter fuselage would about be offset by the shorter length required for the same seating capacity.

On the whole, I am inclined to favour the larger diameter with its additional air of spaciousness and reduced number of seat rows. Incidentally, no passenger would have to sit three-abreast in the tourist accommodation except when more than 40 passengers were carried, at a load factor exceeding 66·6 per cent. In the first-class accommodation, three-abreast seating would happen only at load factors exceeding 80 per cent.

Wing Height

A third major factor for an airline is the wing position (Fig. 6). Following the outstanding success of the high-wing Elizabethan in its qualities of passenger attraction, there has evolved a widely held opinion in favour of this arrangement. The evolution of new and more powerful engines, swinging large-diameter propellers, also favours the high wing because adequate propeller clearance would otherwise make the passenger door-sill exceptionally high off the ground.

Advantages of the high wing from an airline point of view are:—

1. Low loading position of fuselage—speeding turn-rounds and saving expensive steps.
2. Good view for passengers from all seats.
3. No dazzling reflections into the cabin from the wing.
4. A "sunshade" above the cabin.
5. Ease of maintenance because of accessibility of control runs in the roof.
6. Less engineering trestles required for overhaul.
7. Shorter nose-wheel.
8. Lower overall height for hangar doors.
9. Less damage in a belly landing, because the engines and wing are clear of the ground.

Disadvantages include:—

1. Poor ditching characteristics.
2. Slightly heavier structure weight.
3. Problems of main undercarriage stowage.

Summing up the pros and cons, we in B.E.A. believe firmly in the high wing—a view based on practical experience of both types (Fig. 7).

Quite apart from its passenger attractions, the way in which the high wing can help economy of operation

FIGURE 6. B.E.A. Viscount and Elizabethan—showing difference in height of door sills.

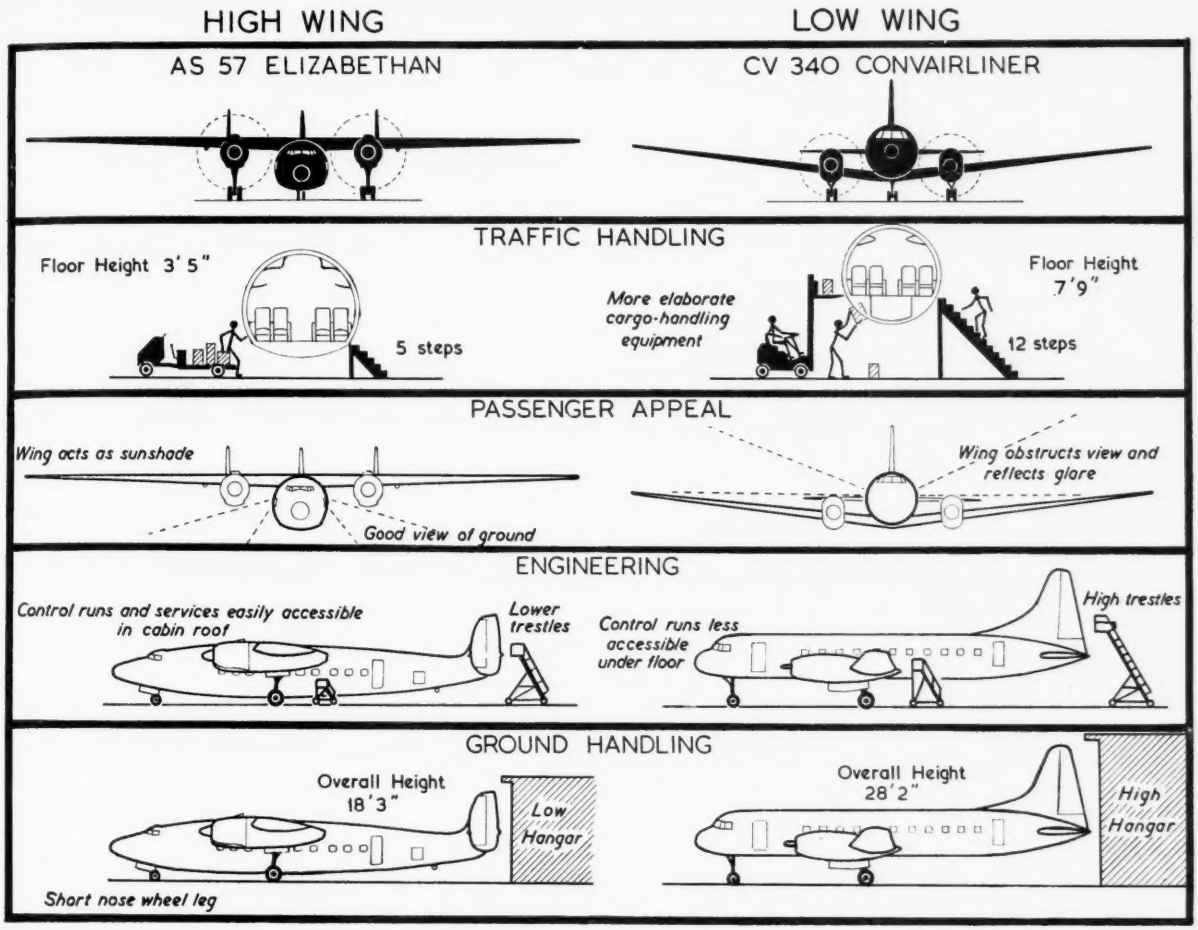


FIGURE 7. High wing and low wing configuration to illustrate high wing advantages.

can be judged from an analysis of turn-round or transit times at airports, especially on short or medium range operations.

Experience has shown that—all other things being equal—the high wing can cut a transit time by between five and ten minutes—depending upon the amount of work to be done on such matters as refuelling, baggage unloading and loading, catering provision and passenger disembarkation and re-entry.

The high wing speeds up the whole process, firstly because service vehicles can drive all round without coming up against the wing, secondly because long steps and fork lifts are not needed and thirdly because access to doors and holds is simple and can begin immediately the aeroplane comes to a stop.

TABLE II

MAXIMUM DAILY UTILISATION ACHIEVABLE

	(14-*hour Working Day*)			
Transit times	100-*mile sector*	200-*mile sector*	500-*mile sector*	800-*mile sector*
20 min.	10·0 hrs.	10·9 hrs.	12·0 hrs.	12·6 hrs.
30 min.	8·7 hrs.	9·7 hrs.	11·3 hrs.	12·3 hrs.
40 min.	7·8 hrs.	8·9 hrs.	10·6 hrs.	11·7 hrs.
1 hr.	6·3 hrs.	7·5 hrs.	9·7 hrs.	10·6 hrs.
2 hrs.	4·1 hrs.	5·2 hrs.	7·3 hrs.	9·5 hrs.

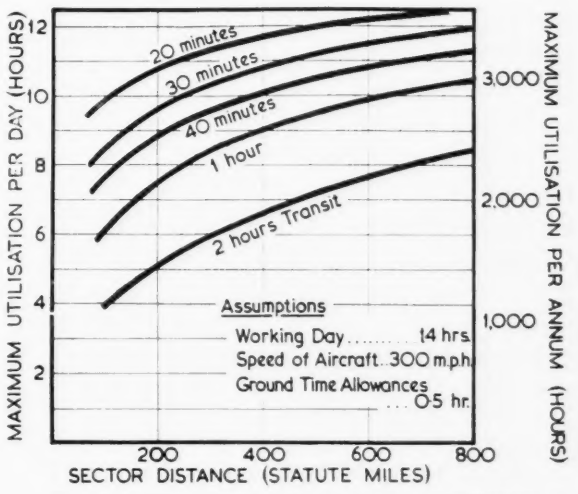


FIGURE 8. Effect of transit time on maximum utilisation.

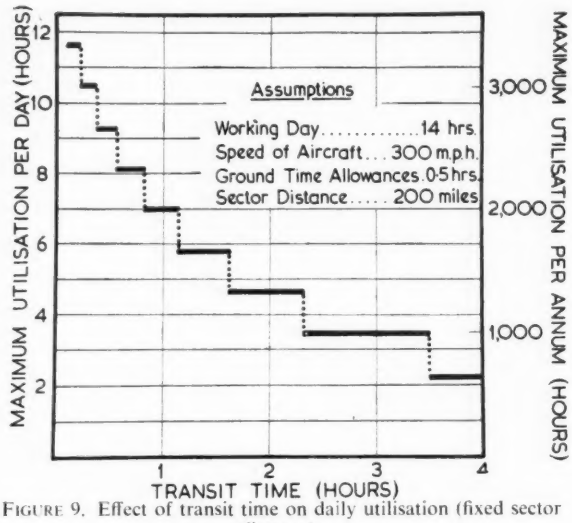


FIGURE 9. Effect of transit time on daily utilisation (fixed sector distance).

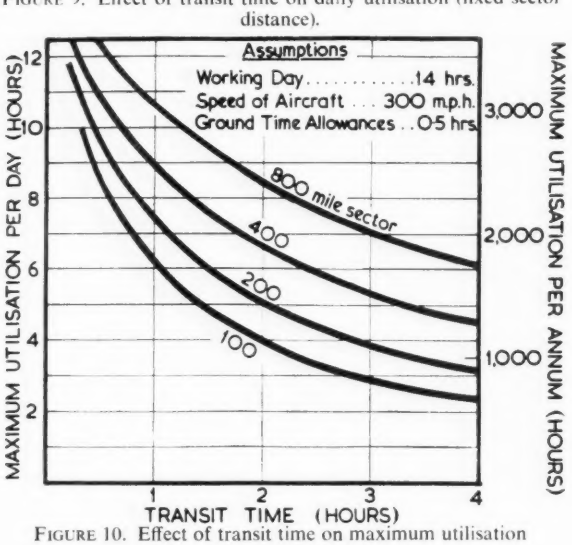


FIGURE 10. Effect of transit time on maximum utilisation (various sector distances).

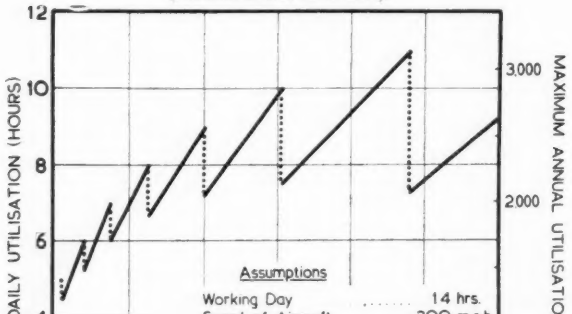

MAXIMUM DAILY UTILISATION (HOURS)
MAXIMUM ANNUAL UTILISATION (HOURS)
Assumptions
Working Day 14 hrs.
Speed of Aircraft 300 m.p.h.
Ground Time Allowances 0·5 hrs.
Airport Transit Time 1 hr
Length of dotted line is block time
Note at indicated sector distance
SECTOR DISTANCE (STATUTE MILES)

FIGURE 11. Effect of sector distance on maximum utilisation (" saw-tooth ").

Transit Time Against Utilisation

How a reduction in turn-round time can improve utilisation, and hence economy, is shown by a study of typical utilisation figures which can be achieved for a 300 m.p.h. aeroplane (Fig. 8).

From Table II two things can be seen—that a high utilisation is possible only at longer stages and with the shorter transit times. Obviously the longer the sector the less the number of transit stops and hence the less the opportunity of losing time. This is one of the reasons for the dis-economy of short hauls. The problem can be seen in a different way (Fig. 9) by plotting maximum achievable utilisation against transit time for a specific sector distance. Thus, at 200 miles, a one-hour transit time will allow seven hours flying in a working day or 2,000 hours per annum*. However, because an extra sector cannot be squeezed in, except with some wider variation in transit time, this same daily utilisation is the maximum attainable with a transit stop of anywhere between 50 minutes and 1 hour 10 minutes. Hence the need for careful scheduling.

Put yet another way (Fig. 10), the longer the sector and the shorter the transit time—up to a point—the higher the practical utilisation.

Incidentally, for a typical modern 300 m.p.h. transport aeroplane of some 55,000 lb. gross weight an additional hour a day's utilisation (about 290 hours a year) is worth about £56,000 of revenue at current rates, assuming an average sector distance of 500 miles. Further, a saving of five minutes on a transit time of one hour over a 200 mile sector is worth nine m.p.h. of additional cruising speed, in its effect on the revenue earning miles achieved in a day's work. The effort to achieve that additional nine m.p.h. in cruising speed from aerodynamic improvement or extra power, would be very great indeed. The lesson for airline operators is thus—*cut down your transit times* on the ground.

Much loose thinking has gone on about utilisation rates in recent years, and there is a natural tendency to state, for convenience, a fixed utilisation rate to be achieved by aeroplanes with widely different cruising speeds and regardless of sector distances flown. This conception is inaccurate, misleading and impractical.

Variable Utilisation Rates

In fact, achievable rates of utilisation will vary about as widely with sector distance as they will for different cruising speeds. The pattern is a jagged "saw-tooth" (Fig. 11) controlled by the maximum, complete, number of sectors which can be flown at each sector distance within the commercially saleable working hours available—which on short hauls in Europe is about fourteen out of the twenty-four. For theoretical comparisons, of course, an expedient generalisation is to file off the saw teeth, as it were, and employ a smoothed curve.

Thus, for a 300 m.p.h aeroplane the following points can be plotted for typical utilisations which can

*Annual utilisation is derived from the daily rate by making allowance for maintenance checks, scheduling demands, commercial timings, weather and dead flying.

be achieved over various sector distances, assuming a transit time of one hour at each stop:—

Sector distance	*Possible number of complete sectors a day*	*Daily utilisation rate*
200 miles	6	7·00 hrs.
400 miles	5	9·00 hrs.
600 miles	4	9·80 hrs.
800 miles	3	9·40 hrs.
1,000 miles	2	7·60 hrs.
1,200 miles	2	8·75 hrs.

In this table, based on regularly spaced sector distances of equal length, as a result of the "saw-tooth" effect the maximum utilisation is in fact achieved at a sector distance of 600 miles with a rate of 9·80 hours a day (2,800 hours per annum). Maximum utilisation at the point of the highest "saw-tooth" is at 960 miles, where a rate of 11 hours a day (3,100 hours per annum) is attainable. Several other variables will, however, affect the issue—such as the practical effect of mixing short and longer sectors to improve results and also by extending the working day so that a number of night services can be scheduled and sold (more in the peak Summer holiday season than in the Winter). But the underlying facts remain.

Economies of Speed

That leads to a further point—the economies of speed. And, because time is one of the chief commodities being sold by Air Transport, speed—both in the air and on the ground—is one of the essential ingredients of economic success.

First then—speed and utilisation. It has already been shown that a high utilisation is, usually, more difficult to achieve with a fast aeroplane than with a slow aeroplane because of the increase of the incidence of transit stops over a specific sector pattern.

Typical figures may be set out thus (Fig. 12) assuming a ground transit time of one hour:

ANNUAL ACHIEVABLE UTILISATION RATES FOR VARIOUS CRUISING SPEEDS

(14 *hour day: Transit time one hour*)

Sector distance	100 *m.p.h.*	200 *m.p.h.*	300 *m.p.h.*	400 *m.p.h.*
100 miles	8·5 hrs.	7·2 hrs.	6·1 hrs.	5·3 hrs.
200 miles	10·0 hrs.	8·5 hrs.	7·6 hrs.	7·0 hrs.
300 miles	10·9 hrs.	9·3 hrs.	8·5 hrs.	8·0 hrs.
400 miles	11·5 hrs.	10·0 hrs.	9·0 hrs.	8·5 hrs.
500 miles	11·9 hrs.	10·5 hrs.	9·5 hrs.	9·0 hrs.
600 miles	12·2 hrs.	10·9 hrs.	9·9 hrs.	9·4 hrs.
800 miles	12·8 hrs.	11·6 hrs.	10·6 hrs.	10·0 hrs.

Although the slower aeroplane can more easily achieve a high utilisation, especially over long distances, that is, obviously, only part of the story. Speed is important competitively, it is essential for punctuality (Fig. 13) and it improves economy (provided that it is gained without extravagance in power) because of the increased earning potential which it offers. Although the fast aeroplane may have a lower utilisation rate, nevertheless it will be able to fly more revenue-earning sectors in a year.

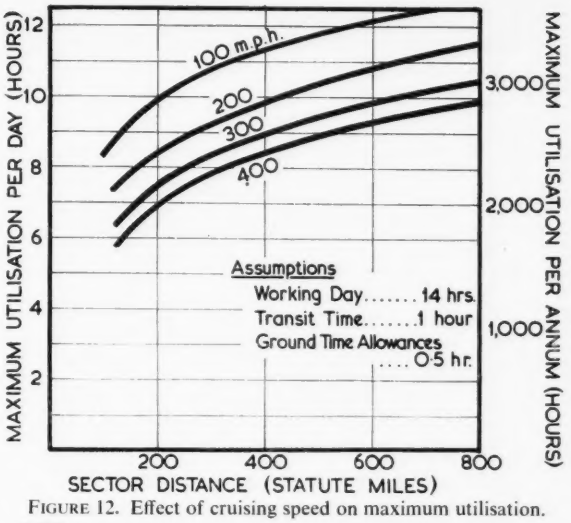


FIGURE 12. Effect of cruising speed on maximum utilisation.

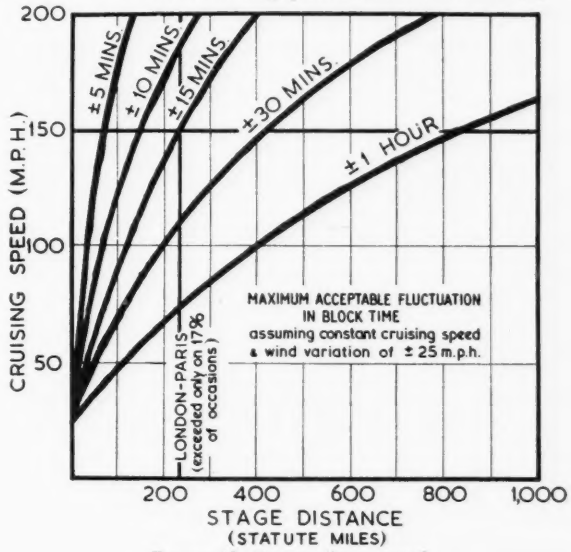

CRUISING SPEED (M.P.H.)
±5 MINS
±10 MINS
±15 MINS
±30 MINS
±1 HOUR
LONDON-PARIS (exceeded only on 1% of occasions)
MAXIMUM ACCEPTABLE FLUCTUATION IN BLOCK TIME assuming constant cruising speed & wind variation of ±25 m.p.h.
STAGE DISTANCE (STATUTE MILES)

FIGURE 13. Punctuality v. speed.

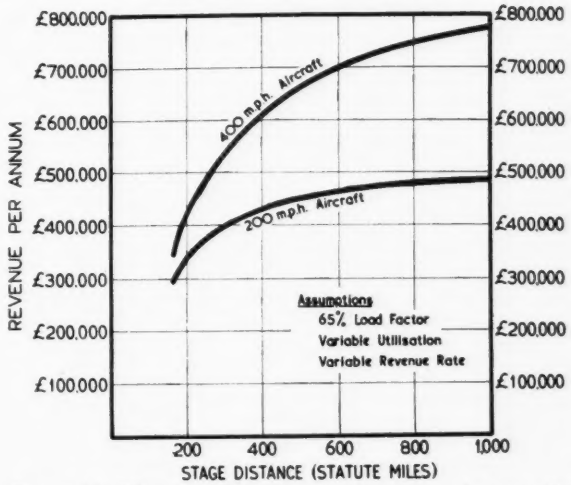


FIGURE 14. Effect of cruising speed on revenue earning potential (200 m.p.h. v. 400 m.p.h.).

Revenue Earning Potentiality

The economies of speed can be seen from an analysis of revenue earning capacity comparing two similar, but hypothetical aeroplanes, one cruising at 200 m.p.h., the other at 400 m.p.h.

Again the achievable results are tabulated, comparing the aircraft over sector distances of 200 and 800 miles, both with a 65 per cent. load factor on 50 seats and assuming a 14 hour working day and a one hour transit time for each (Fig. 14).

	200 *miles*	800 *miles*
Revenue rate per passenger mile (B.E.A. International Rate 1954)	7.80d.	6.10d.
Revenue rate per seat mile (at 65 per cent. load factor) ...	5.07d.	3.96d.
Daily utilisation rate		
(200 m.p.h. aeroplane) ...	8.5 hrs.	11.6 hrs.
(400 m.p.h. aeroplane) ...	7.0 hrs.	10.0 hrs.
Equivalent annual utilisation rate		
(200 m.p.h. aeroplane) ...	2,430 hrs.	3,310 hrs.
(400 m.p.h. aeroplane) ...	2,000 hrs.	2,860 hrs.
Sectors performed per annum		
(200 m.p.h. aeroplane) ...	1,620 sectors	730 sectors
(400 m.p.h. aeroplane) ...	2,000 sectors	1,145 sectors
Block speed (30 minutes ground time allowances)		
(200 m.p.h. aeroplane) ...	133 m.p.h.	178 m.p.h.
(400 m.p.h. aeroplane) ...	200 m.p.h.	320 m.p.h.
Revenue earned per annum		
(200 m.p.h. aeroplane) ...	£341,000	£486,000
(400 m.p.h. aeroplane) ...	£422,000	£755,000

In this example, on the short sector the faster aeroplane can earn £81,000 (24 per cent.) more annual revenue than the slower aeroplane (the block speeds are 133 m.p.h. and 200 m.p.h. respectively) whereas, on the longer sector the faster aeroplane earns £269,000 (55 per cent.) more revenue (the block speeds are, then, 178 m.p.h. and 320 m.p.h. respectively). The higher speed is, hence, even more worth while over the longer sectors.

Economics

So we come to the essence of the business and the primary reason for new and better aircraft—Economics.

A realistic assessment of the economics of any new aeroplane relative to sector distance must be based on the feeding in of the right variables—some of the variable factors being in fact those which have been deemed to be constant in earlier analyses.

The primary factors which vary with sector distance are, in practice:—

1. *Payload* (replaced by fuel on longer sectors).
2. *Block speed* (influenced by ground time allowances and percentage of time spent in climb and descent).
3. *Utilisation* (influenced by block speed, transit time, and length of the commercial working day)
4. *Total Cost ratio* (relative to "Aircraft Costs")*.
5. *Revenue Rate* (modified by Load Factor).

Taking all these variables (Fig. 15) into account we require to know six primary economic figures for any aeroplane at various sector distances.

1. *Cost per Aircraft Mile* (of primary importance when traffic is scarce).
2. *Cost per Seat Mile and per Ton-Mile* (of primary importance when traffic is dense).
3. *Number of passengers to Break Even* (the fewer the better).
4. *Total Revenue per annum.*
5. *Total Cost per annum.*
6. *Annual Profitability.*

Taking, for simplicity, an Elizabethan on a sector distance of 400 statute miles and listing the primary factors in the foregoing order, the following basic assumptions can be set down as:—

Payload—47 passengers plus 2,740 lb. of freight, mail and excess baggage.

Block Speed—189 m.p.h. resulting from a cruising speed of 230 m.p.h. on 1,150 b.h.p. per engine at 15,000 feet.

Utilisation—2,230 hours. On a transit time of one hour the maximum achievable rate has been reduced by 22 per cent. to allow for weather cancellations, unscheduled maintenance, "cushion" time on transit and commercial timings.

Total Cost Ratio—Relative to Aircraft Costs—162: 100.

Revenue Rate—

Passenger—7.0 pence per passenger mile at 64 per cent. load factor.

Deadload—66.2 pence per passenger mile at 59 per cent. load factor.

Total 63 per cent. load factor.

The following "Aircraft Costs" are based on these assumptions:—

Basic annual cost (per annum): £29,900.

Hourly cruising cost (per hour): £50 10s. 0d. (at 2,230 hours = £112,615 per annum).

Take off and landing cost (per sector): £8 18s. 0d. (at 1,060 sectors = £10,500 per annum).

The final cost and revenue picture which emerges from this analysis can be set out as follows:—

Total cost per aircraft mile: 11.71 shillings.
Total cost per ton mile: 24.1 pence.
Total cost per seat mile: 2.99 pence.
Total passenger revenue per aircraft mile: 17.50 shillings (at 64 per cent. load factor).
Number of passengers to break even on total costs: 20.1 (passenger load only).
Payload tons to break even on total costs: 1.95 tons (16 passengers plus 880 lb. of deadload).
Total passenger revenue per annum (at 64 per cent. passenger load factor): £370,000 per aircraft.
Total revenue per annum (at 63 per cent. load factor): £465,000 per aircraft.
Total cost per annum: £247,000 per aircraft.
Annual profitability (passengers only): £123,000 per aircraft.
Annual profitability (total load): £222,000 per aircraft.

*"Aircraft Costs" are defined as those influenced only by the characteristics of the type of aeroplane concerned. "Total Costs" are "Aircraft Costs" plus "Airline Costs," the costs influenced by the characteristics of the airline. The ratio of "Aircraft Costs" to "Total Costs" varies with stage length, the "Airline Costs" becoming progressively smaller with increased sector length because of the reduction in station costs.

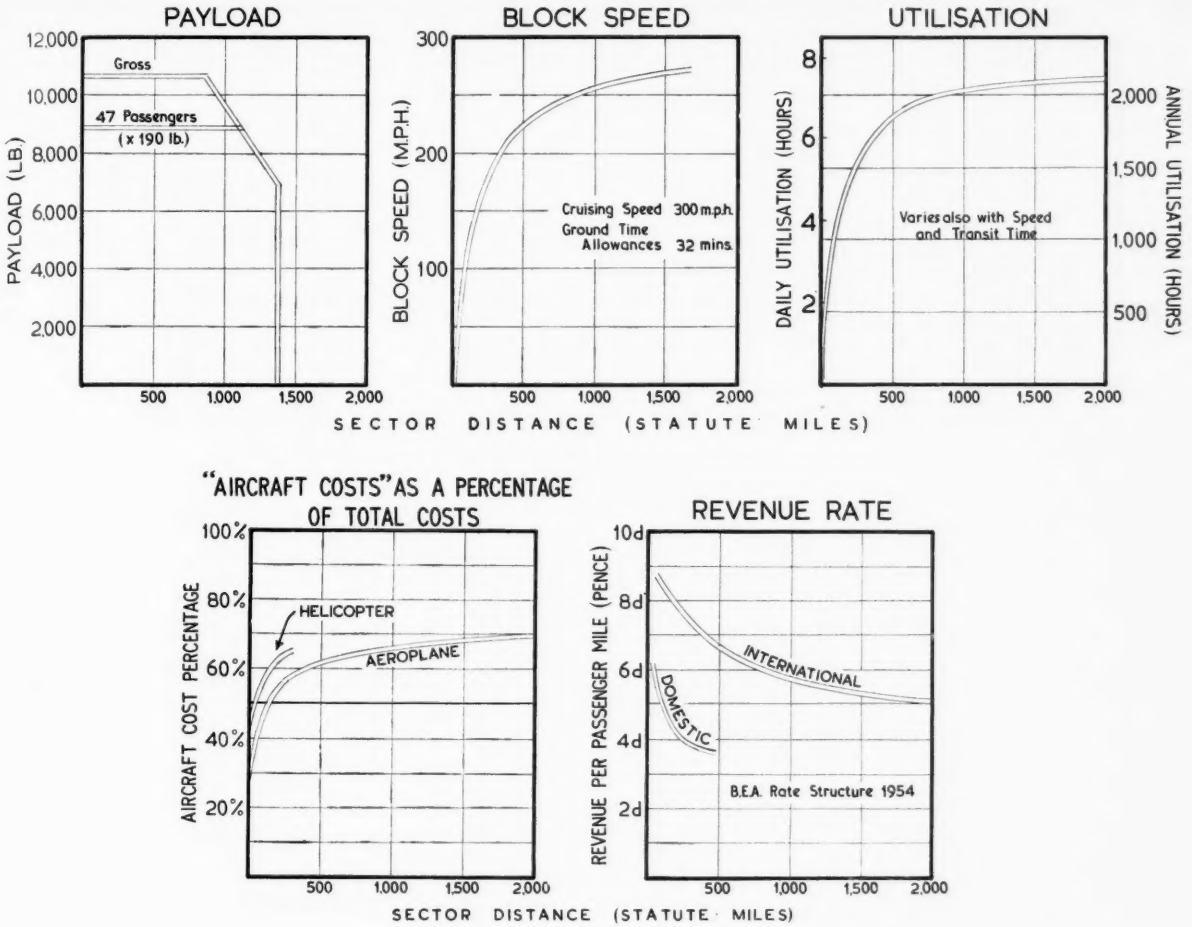


FIGURE 15. Variable factors in assessing aircraft profitability.

These figures bring out several interesting points—especially when plotted over varying sector distances (Figs. 16, 17, 18 and 19). Perhaps the most interesting is the way in which the various factors combine to show a nearly constant total cost per annum.

In fact, for the Elizabethan, the total cost per annum at a 200 mile sector is £245,000 and at a 1,000 mile sector £240,000, which is only two per cent. less. The total cost is thus almost static for all sectors.

The annual passenger revenue at 200 miles is £292,000, at 500 miles £384,000 and at 1,000 miles £388,000, peaking, in fact, at 800 miles—influenced not only by payload and block speed but also by revenue rate.

Comparing the two, the Annual Profitability of the Elizabethan reaches its maximum over a sector distance of 800 miles where, at a 64 per cent. load factor, a net profit of some £151,000 per annum can be earned by each aircraft at an annual utilisation rate of 2,470 hours.

At the other end of the scale, the break-even point at 64 per cent. load factor, is reached at a sector distance of 180 miles. Short of this distance losses mount heavily. A small increase or decrease in load factor or revenue rate at these short distances will have a powerful effect on potential profit or loss because of the steepness of this part of the curve.

These short sector distances are, indeed, an operator's headache.

Helicopters

That is, of course, where the helicopter comes into the picture. Because it can operate directly between city centres the helicopter can save a great deal of time on most journeys of up to 250 miles. The fixed-wing aeroplane is severely handicapped by the slow surface journey from the airports to the cities (Fig. 21). Thus, the faster the helicopter the longer the sector over which it can match the aeroplane in elapsed time between city centres.

Helicopter costs, however, are inevitably high. On the basis of available information the cost and fare necessary to break even can be tabulated of a hypotential 38-passenger helicopter of some years hence and the present-day Viscount, over short sectors.

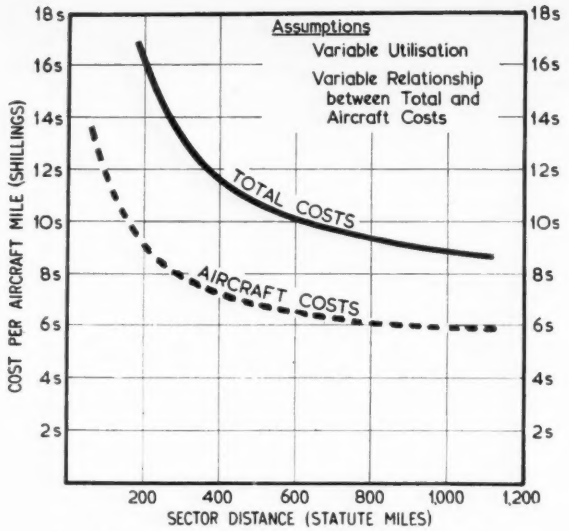


FIGURE 16. Aircraft and total costs per aircraft mile. (Elizabethan).

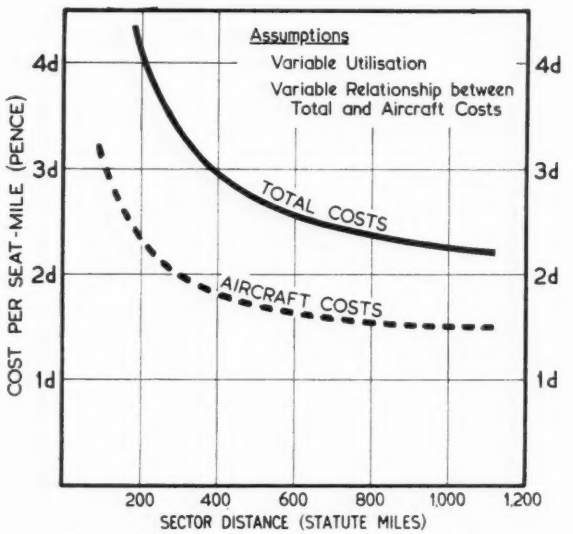


FIGURE 17. Aircraft and total costs per seat mile. (Elizabethan).

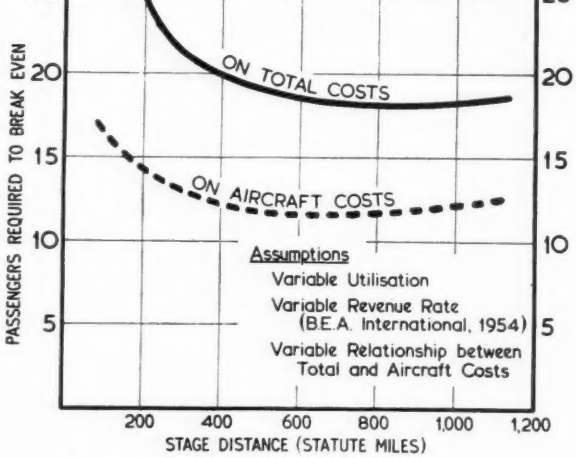


FIGURE 18. Number of passengers to break even. (Elizabethan).

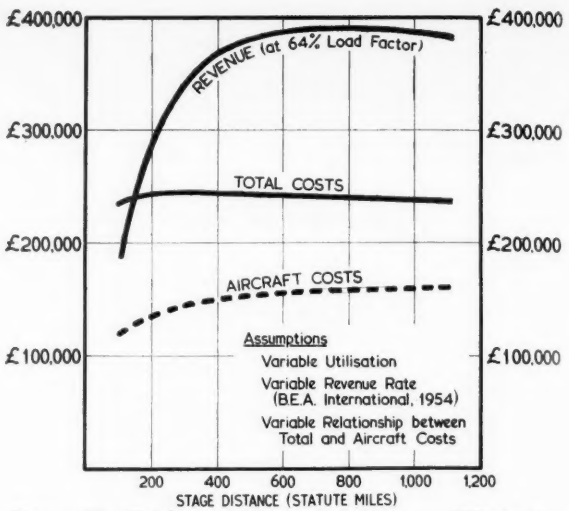


FIGURE 19. Total cost and revenue per annum (Elizabethan).

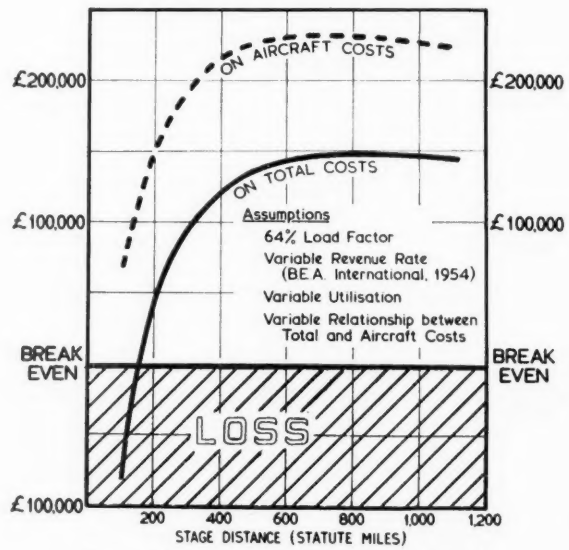


FIGURE 20. Annual profitability (Elizabethan).

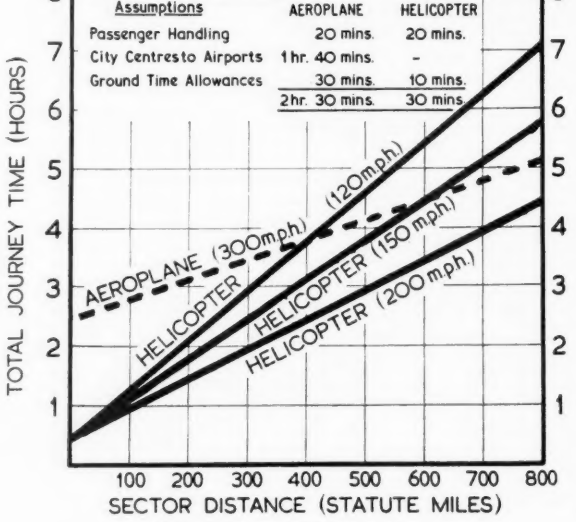


FIGURE 21. Total journey time.

The analysis is as follows:—

	Turbine Aeroplane	*Turbine Helicopter*
Number of passenger seats ...	47	38
Cruising speed	300 m.p.h.	150 m.p.h.
Assumed load factor	65 per cent	65 per cent
Annual utilisation at 100 miles	1,360 hrs.	1,725 hrs.
200 miles	1,690 hrs.	2,000 hrs.
Block speed at 100 miles ...	116 m.p.h.	130 m.p.h.
200 miles ...	167 m.p.h.	140 m.p.h.
Time between city centres		
100 miles ...	2 hrs. 21 min.	1 hr. 15 min.
200 miles ...	3 hrs. 42 min.	1 hr. 56 min.
Ratio of Total Cost to Aircraft Cost 100 miles	100:52	100:58
200 miles	100:56	100:64
Total cost per aircraft mile		
100 miles ...	31.4 shillings	19.0 shillings
200 miles ...	18.2 shillings	14.8 shillings
Total cost per seat mile		
100 miles ...	8.04d.	6.00d.
200 miles ...	4.66d.	4.95d.
Total annual cost 100 miles ...	£248,000	£214,000
200 miles ...	£257,000	£209,000
Revenue rate per passenger mile (between city centres)		
100 miles ...	9.65d.*	8.45d.
200 miles ...	8.40d.*	7.80d.
Annual profitability on total costs 100 miles	£57,000 loss	£22,000 loss
200 miles	£40,000 profit	£2,000 profit
Revenue rate necessary to break even 100 miles	12.37d.	9.25d.
200 miles	7.18d.	7.62d.

*The air fare rate is assumed to be the same for aeroplane and helicopter. The higher aeroplane revenue rate between city centres results from the five shilling bus fares to and from the airports.

From this (Figs. 22, 23, 24 and 25) we can see that the helicopter needs a higher revenue rate to break even than the aeroplane on all sector distances of more than 150 miles and the question is whether the public would be willing to pay the extra fare per mile necessary to cover the costs. The Viscount can "self-subsidise" very short sectors from profit over longer routes—the helicopter cannot do this because it gets steadily more

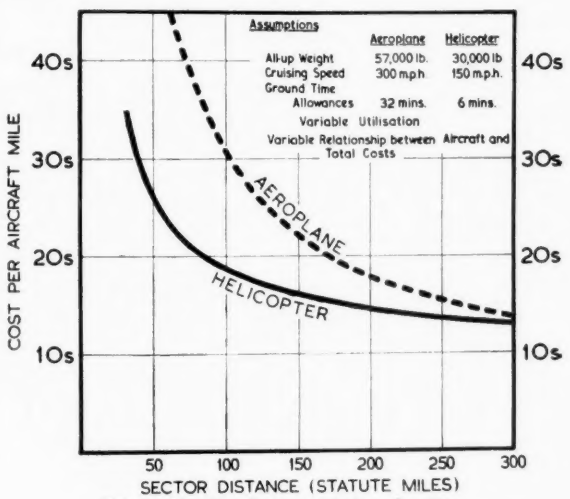


FIGURE 22. Total costs per aircraft mile.

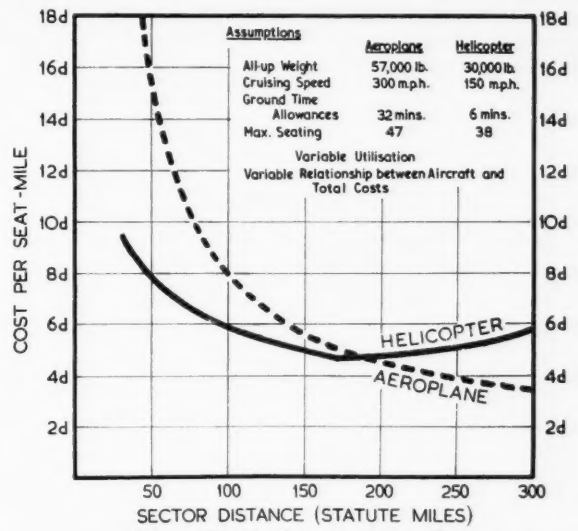


FIGURE 23. Total costs per seat mile.

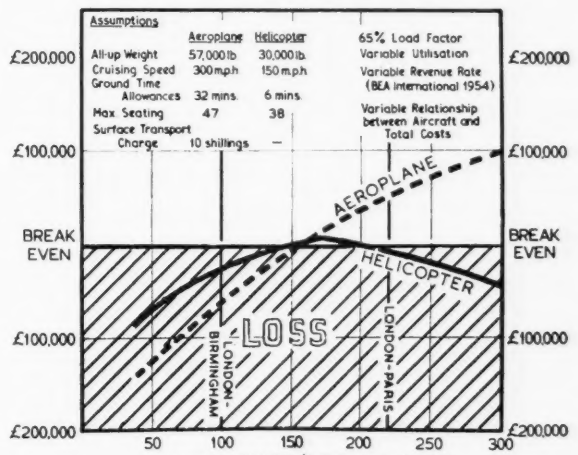


FIGURE 24. Annual profitability.

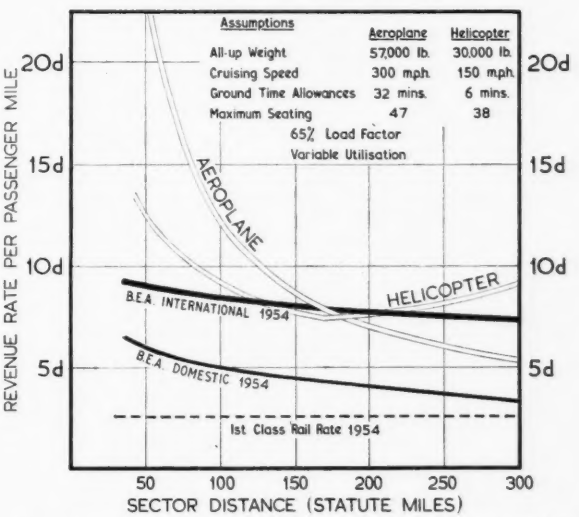


FIGURE 25. Helicopter *v.* Aeroplane. Revenue rates required to break even on total costs

expensive to operate at distances above about 300 miles. Hence the dilemma.

Points worth noting on this helicopter comparison include the following:—

1. The helicopter can achieve higher utilisation than the aeroplane on a given stage length because of its shorter transit times. This improves its relative economics.
2. The "Airline Costs" associated with fixed-wing operations are relatively higher than those which can be reasonably forecast for a helicopter operation. This means that the Total Costs of the helicopter will be proportionately less in relation to its "Aircraft Costs" than will be those of the aeroplane.
3. The cost of providing rotor stations including their lighting and radio installations, should be substantially less than that of airports for fixed-wing aircraft. This fact should be reflected in lower landing fees.

My belief is that small scale helicopter services will begin during the next decade at relatively high fares, but that losses upon them will have to be subsidised out of profits from fixed-wing services on longer routes with which the helicopter service will be integrated.

Prospects Ahead

These, then, are some of the problems and possibilities which an airline must have in mind when considering new equipment and its future operation. Essentially it must be looking eight to nine years ahead to try to discern—even dimly—the needs of the future. If heed is not given to these future needs today, then when the time comes the competitive equipment will not be there to meet them.

From the points I have discussed—and with emphasis on aspects of personal opinion—several basic factors do, I suggest, emerge.

(*i*) The forward-looking airline operator must plan some nine years ahead of his operational requirements—a tall order.

(*ii*) For medium stage operations—
- (*a*) the propeller-turbine power-plant is the most attractive proposition,
- (*b*) four engines are required,
- (*c*) high-wing is desirable,
- (*d*) a wide fuselage has advantages.

(*iii*) Rates of annual utilisation are essentially variable with both cruising speed, sector distance and transit time.

(*iv*) Short transit times are of primary economic importance to any airline and design to speed transit times is likely to bring big economic gains—hence one of the attractions of the high wing.

(*v*) Speed spells—
- (*a*) punctuality,
- (*b*) high earning potential,
- (*c*) commercial attractability,

and hence can be economically important.

(*vi*) Profits are almost impossible to achieve with fixed-wing aircraft on sector distances short of about 150 miles at present fare levels. Profits, however, can be considerable with fixed-wing aircraft for sector distances of 400 miles and upwards.

(*vii*) The sphere of the helicopter is potentially between 50 and 250 miles with the likely best economic distance between 150 and 200 miles. A helicopter revenue rate of around tenpence a mile will be needed to cover total costs, provided the traffic will pay this price.

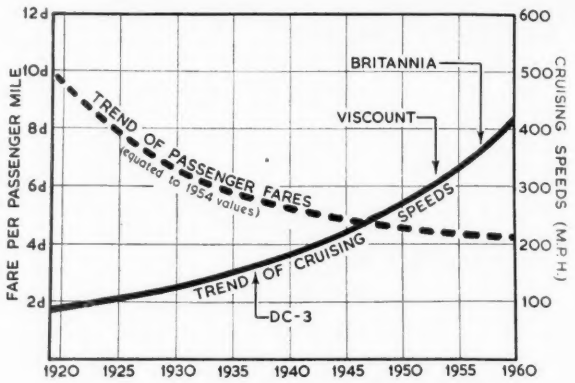


FIGURE 26. Trends in air transport cruising speeds and passenger fares.

In a swiftly moving business, subject to radical technological changes, the present is always a challenge and the future full of boundless possibilities. The problem is to guess right. In such aircraft as the Viscount we are in the lead today. Our task is to stay there—a combined operation for operator and manufacturer in unison.

Peering warily into that crystal ball one can discern only two things with clarity—a steady upsurge in the demand for air transport and the gradual fade out of the piston engine. The trends which have been developing are encouraging. While fares have been coming down steadily over the years, measured in equivalent money values, cruising speeds have been going up as steadily (Fig. 26). Compared with 20 years ago, fares are some 30 per cent. lower whereas cruising speeds are double what they were in 1935—and are still going up.

Looking ahead one can distinguish among the mists of the more distant future, new forms of propulsion which will make vertical flight an economic reality, opening up new horizons for the economic development of a business which will always owe much to the inspired endeavours of the pioneers—among whom we commemorate especially

"Mitchell of Supermarines."

The Design of Small Jet Engines

by

H. S. RAINBOW

(Chief Project Designer, Armstrong Siddeley Motors Limited)

1. Introduction

The whole process of designing an aero engine, from the original concept to the production of the first of the type, called a prototype, normally takes about two years.

The prototype design may originate from proposals put forward by the engine maker from specifications for military aircraft engines, issued in the United Kingdom by the Ministry of Supply, or from the Aircraft Industry.

It is not usual for engines to be designed specifically for civil aviation requirements. More often they are adaptations of military engines de-rated to increase their reliability, and to extend the overhaul period. With the growth of civil transport and the development of guided missiles, it is possible that this state of affairs may be reversed and engines for civil aircraft may become more important than those for Service use. At the present time, it is difficult to foresee a potential civil or private aircraft engine market that would justify the cost of designing and developing a small jet engine on that score alone.

The design of a modern aircraft engine is the work of many specialists and, broadly speaking, implies the knitting together of a set of thermodynamic, aerodynamic and mechanical designs to achieve a given function or operational objective. The selection of these designs, which are dependent on each other, is influenced by many complex and variable considerations which must be examined together; the choice being dependent, not only on the performance required from the engine, but on many other factors including installation, safety, manufacture and reliability. These features, and perhaps many others, must be carefully evaluated against the background of what the engine is expected to do; and finally be appraised by a balance of intuition and judgment based on experience.

The final criteria are specific fuel consumption, specific thrust and specific weight, their relative importance depending upon the operational role of the aircraft.

It is the object of this paper to discuss the many choices that must be made in the preparation of a design for a turbo-jet engine and to try to disentangle, by selection and elimination, the many variables that affect the final arrangement of the design. Attention will be concentrated on the design of small jet engines within the thrust range of 300 to 3,000 lb. Above this, most engines are in the medium or large category and anything below in the very small or midget class. This may not be strictly true and, of course, there are the marginal sizes, but it is quite unimportant as the design procedures discussed apply, for the most part, to the design of turbo-jet engines of almost any size.

Section Lecture given before the Society on 2nd November 1954.

2. The Operational Requirements

Before beginning any design study, a flight specification must be laid down to say what the engine is expected to do.

It is possible that the specification will outline a requirement for an engine for a light weight interceptor fighter, an advanced trainer, or for a guided missile; and it may well be that the engine will be required to fulfil more than one of these roles. Indeed, it will be more than wise if those responsible for the design make quite sure that it can do so, for operational requirements are ever changing and may do so even during the development of the design. Moreover, an engine designed for a specific mission and in production will often be chosen and adapted to another role, not because it is the most fitting, but because it is the most expedient thing to do.

The flight specification usually will indicate the maximum and cruising speed and altitude, the service ceiling, the thrust, either at take-off or at the cruise rating, and an estimate of the specific fuel consumption required.

It is probable that the specification will also include the maximum diameter, length and net dry weight. It may also require special provision for anti-icing, protection from damage, or particular structural features to meet excessive or unusual loadings, either in flight or when landing, such as might occur in a pilotless aircraft. In addition, the engine may be required to operate vertically, or make available large quantities of air for lift augmentation, aircraft de-icing or other aircraft services. It would not be unusual for an engine to be adapted for all of these services and, if the size, weight and specific fuel consumption are about right, it may be employed to drive a helicopter rotor, either through a free turbine and a reduction gearbox, or by providing compressed air or hot gas.

Such a formidable list of requirements is not at all exceptional and, usually, it will be wise to take these possibilities fully into account during the original concept of the design.

2.1. THE FLIGHT SPECIFICATION

It is usual for the flight specification to exert an over-riding influence on the pattern of the design. In some instances, the requirements may be so severe that most, or all, of the possible designs are eliminated, or they may be so lenient that many designs can qualify.

The forward speed, the cruising altitude, the frontal area, the specific weight, and the specific fuel consumption generally are of first importance. To a great extent they are interdependent, but for convenience of explanation they are presented separately here.

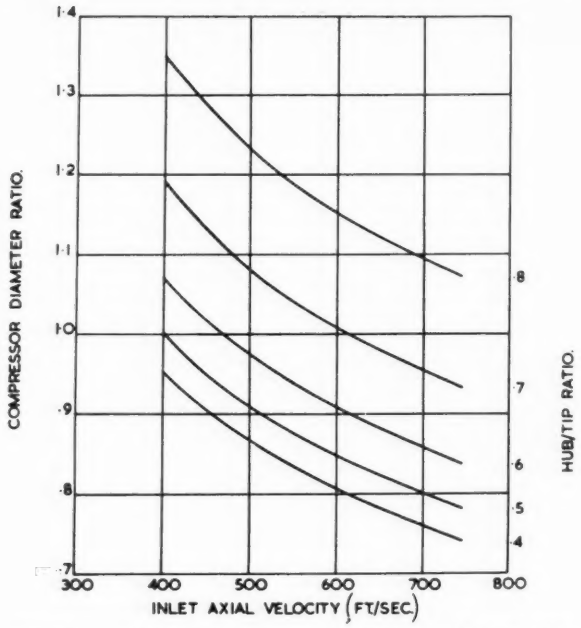


FIGURE 1. Variation of compressor diameter with inlet axial velocity. Constant mass flow.

3. The Influence of Forward Speed

The forward speed has an important influence on the size and weight of a jet engine. It affects the choice of pressure ratio and turbine inlet temperature, the configuration and structure of the design, and the choice of materials.

If the engine is required for very high forward speeds of short duration, it is usual for low frontal area, high specific thrust and low specific weight, to be more important than specific fuel consumption. In this case, one would be anxious to obtain the maximum air mass flow per unit of frontal area, to have as few stages as possible, in both the compressor and the turbine, to keep down the weight, and to run the turbine at the highest possible temperature to increase the thrust.

For low frontal area the choice would fall logically on the axial flow compressor, and interest would centre on the annular area immediately preceding the inlet guide vanes, through which all the air entering the compressor must pass.

For a given diameter the annular area is controlled by the permissible blade length of the first row rotor, which is the difference in diameter between the root and the tip, more commonly known as the hub-tip ratio.

The air mass throughput, at a given intake density, will be a function of the annular area and the axial velocity at the entry to the compressor; and it is of interest to note how these two parameters influence the diameter of the engine.

Figure 1 shows the influence of both the hub-tip ratio and the inlet axial velocity on the outside diameter of the compressor.

Bearing in mind that as few stages as possible, in both the compressor and turbine, will be required to keep down the weight of the engine, it is important to note the influence of pressure ratio, not only on weight, but on the diameter of both the combustion chamber and the turbine to ensure that these do not exceed by too great a margin the frontal area of the compressor. It may be found expedient to choose a pressure ratio that will favour these diameters at the expense of lengthening the compressor. Bearing in mind that increasing the pressure ratio will also improve the fuel consumption, the small increase in the weight of the engine, to keep down the frontal area, may not be quite so serious after all. (*See* Figs. 2 and 3.)

In planning for long duration, specific fuel consumption will be more important than specific weight and specific thrust, and the compression ratio and turbine inlet temperature can be chosen, with more freedom, to give greater economy.

Such a requirement generally will favour a high compression ratio and a moderate turbine inlet temperature, perhaps in the region of 7 : 1 and 1,150°K., but if the engine is a very small one, it may not be possible to use such a high pressure ratio because of the small size of the blades in the higher pressure stages. Thus, at the present state of the art, the small engine cannot achieve such a low specific fuel consumption as the larger engine, and is more likely to suffer additional losses at high altitude due to critical Reynolds number effect.

If high forward speeds are envisaged at low level, attention will have to be paid to the effect of the ram pressure and the pressure ratio, on the maximum temperatures and pressures occurring within the engine.

The compressor casing, the combustion chamber, and the jet pipe will all require strengthening to withstand the high internal pressures, and the effect of the higher air temperature on any light alloy parts used in the construction of the engine must be considered.

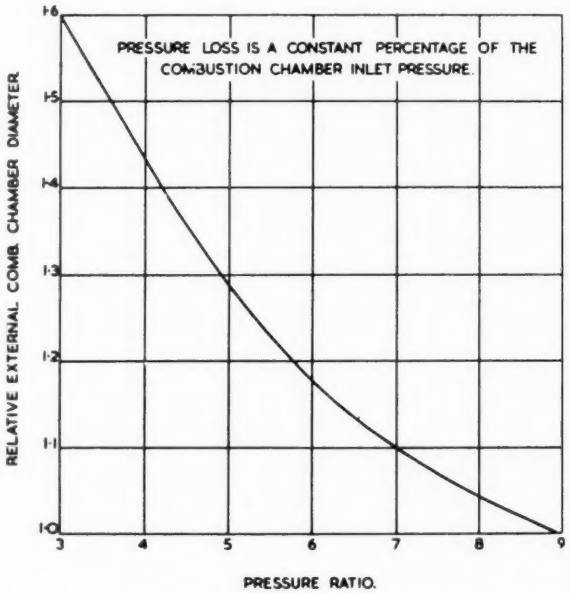


FIGURE 2. Variation of combustion chamber diameter with pressure ratio.

In this connection, the compressor will require particular attention at the high pressure end, and in some instances it may prove desirable to adopt an all-steel construction.

If the high forward speeds are envisaged only at high altitude, it may be that the engine can be designed to be structurally safe at the design altitude, and then be de-rated at sea level by imposing a restriction on forward speed. In this way the maximum internal pressures and gas bending loads on both the compressor and turbine blading will be reduced and a reduction in structural weight will be achieved.

So far the main consideration has been of the axial flow engine, whereas there are some very attractive little engines employing either centrifugal or mixed flow compressors, for which similar design conditions must apply.

Speaking generally, the centrifugal jet engine is not well adapted to achieve both high forward speeds and low fuel consumption, but there are other considerations which may prove an exception to this rule.

When manufacturing economy, simplicity or expendability is required, the small centrifugal holds a high place and can offer advantages that may outweigh the inherent disadvantages of lower specific thrust and higher specific fuel consumption; more will be said about this later on.

4. The Influence of Altitude

The maximum altitude at which the engine is required to operate may influence the choice of pressure ratio and turbine inlet temperature; but the forward speed and the specific fuel consumption usually exert an over-riding influence. It is perhaps sufficient to say that the thermodynamic design must ensure that the engine can give the required power and specific fuel consumption at the design altitude.

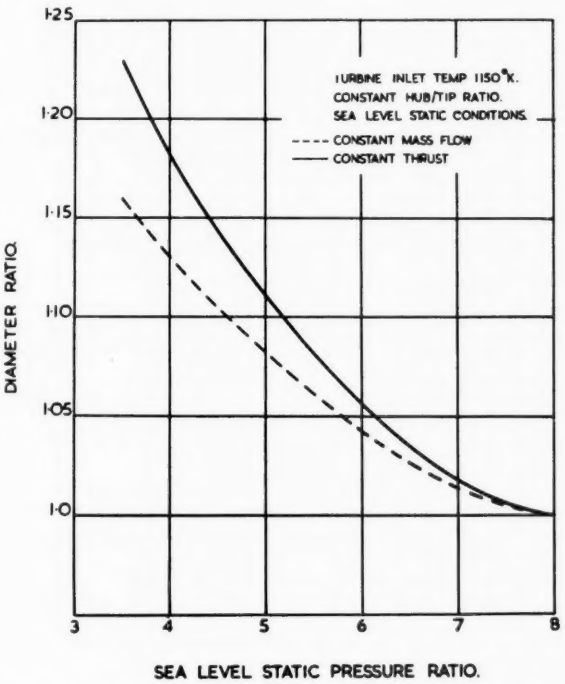


FIGURE 3. Variation of maximum turbine diameter with design pressure ratio. Constant outlet Mach number.

Once this thermodynamic choice has been made, the operational altitude has little effect on the actual layout of the engine, but it must be taken into account in the design of the combustion system, the aerodynamic design of the axial flow compressor and any arrangement that may be made for engine or oil cooling.

Both the centrifugal and the axial flow engine are liable to suffer from combustion instability, the possibility of flame blow-out, and the difficulty of relighting. The remedy usually is intensive development and, in normal circumstances, this does not affect the fundamental design of the engine very much.

The centrifugal engine, as a rule, does not suffer serious losses arising from critical Reynolds number effect at altitude, but the axial flow compressor is sensitive to this defect and the blade chords must be fixed with this in mind.

In the high pressure stages, stressing considerations usually make wide chord blades essential, and these operate in a region of such turbulent flow that generally they do not suffer from critical Reynolds number effect; but the low pressure stages, perhaps the first three blade rows, sometimes require a chord in excess of that required by stressing considerations alone, to prevent serious losses occurring at the higher altitudes.

In engines designed for high supersonic speeds, where there is a considerable increase in intake density due to the ram pressure, this loss may not arise so that the blade chords may be reduced, to shorten the compressor and reduce the weight of the engine.

The blade chords influence the weight and length of the compressor and thereby the whirling speed of supporting shafts, where these are used, and it may be a major operation of redesign to modify the compressor if the engine should be required later to operate at a higher altitude. Therefore, it will be wise, when there is no design limitation on the overall length of the engine, to design the compressor blading to be free from critical Reynolds number effect up to the highest possible altitude.

Figure 4 shows the relative blade chord required to maintain Reynolds number constant with altitude and this increase obviously affects the length of the compressor. In practice, lengthening the compressor to maintain the compressor performance up to the maximum altitude may impose too great a weight penalty on the engine, and it may be necessary to compromise by imposing a limitation on the minimum forward speed with increase in altitude.

5. Lubrication and Cooling

It is common practice in aircraft gas turbines to use air drawn from the compressor for bearing cooling, in conjunction with a throw-away oiling system. This arrangement is very simple and has worked very well. The oil consumption is negligible, being approximately a half pint per hour for each rotor bearing, and a total

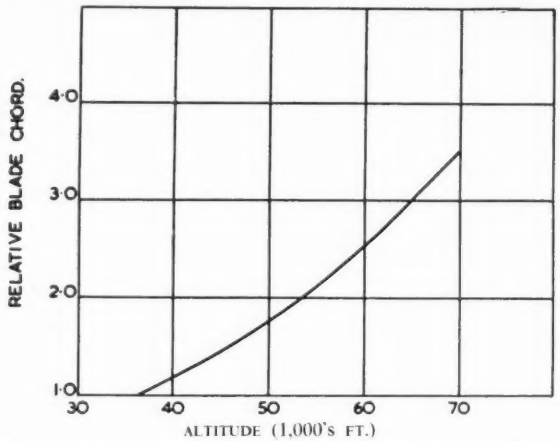


FIGURE 4. Increase in blade chord with altitude to maintain constant Reynolds number. Constant indicated aircraft speed of 200 m.p.h.

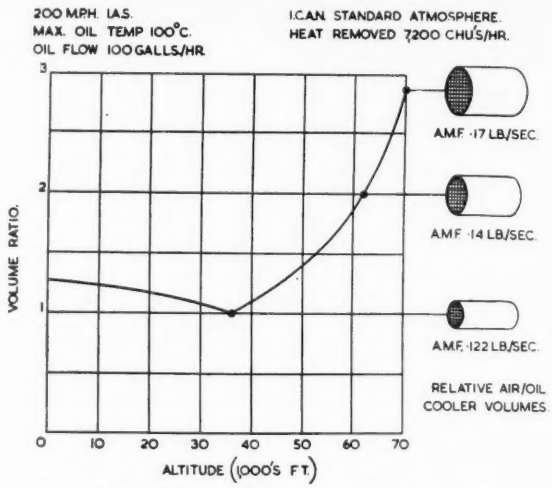


FIGURE 5. Effect of altitude on air/oil cooler volume.

air consumption of no more than $\frac{1}{4}$ lb. per hour for quite a large engine, the actual amount depending, of course, on the pressure ratio, the bearing temperature and the operating conditions.

It is possible, however, at very high altitudes, say 45,000 ft. and above, particularly with regard to the turbine bearing, that air cooling may not suffice. At the lower levels compressed air is relatively cheap and easy to obtain, but at the higher levels it can be a comparatively rare and expensive commodity; and may not easily be made available in sufficient quantities to cool the bearings. It is a reasonable supposition that the heat generated in the bearings or soaked up from the hot end of the engine, is substantially the same at any fixed operating conditions, irrespective of altitude, whereas the cooling effectiveness of the air falls with increase in altitude.

It is possible that, up to a certain level, the reduction in heat transfer due to the lower density may be compensated by the drop in air temperature, the level depending on the actual conditions obtaining within the engine, but above this a steady decrease in the effectiveness of the air cooling system will occur.

One remedy is to counter this by employing a full flood lubrication system, that is one where cooling air is not employed and where excess heat, generated in the bearing, is conducted away by passing an appropriate quantity of oil through the bearing. On low pressure ratio engines, it may be necessary to do this only for the turbine bearing, but in high pressure ratio engines, say 7 : 1 and above, or those designed for "high supersonic" speeds, it may be necessary to full flood both the turbine and the compressor bearings, to avoid lubrication troubles arising from excessive bearing temperature.

In some instances it may be necessary to employ an oil cooler. If this is designed to be effective under tropical conditions at sea level, it will probably be effective up to 40,000 ft., or more, according to the individual design; above this the size of the cooler for a given rate of heat dissipation will increase rapidly, and if the engine is required to fly at very high altitudes, say 60,000 or 70,000 ft., the cooler may become inconveniently large and it may be necessary to resort to other methods of cooling the oil. One such is the fuel oil cooler, where the fuel is circulated through the oil cooler before passing to the engine. The heat picked up from the oil passes to the combustion chamber with the fuel, and so, thermodynamically, is not lost to the cycle.

The quantity of fuel passing through the cooler at sea level will normally be many times that required to cool the oil. It is usual, therefore, to design the cooler for the altitude rating and to by-pass the excess fuel available at the lower altitudes.

It is possible, however, at very high altitudes, particularly on a high pressure ratio engine, or one designed for high supersonic speeds where there is a high ram temperature rise, that a point may arise where there is insufficient fuel passing through the cooler to cool the oil. This is unlikely to occur at present engine ratings if the fuel system is designed to permit a fuel temperature in the range of 150°C., but at high supersonic speeds at extreme altitudes this point is worthy of special consideration. (*See* Fig. 5.)

6. Power Take-Off

It is not unusual for power to be taken from the engine, either in the form of shaft power for driving aircraft accessories, or in the form of compressed air for actuation of engine auxiliaries or for aircraft services: in this connection there are one or two points that are worthy of special mention.

In the case of air taken from the compressor for pneumatic jacking systems, such as might be used for the actuation of valves, variable nozzles, retractable debris guards, and so on, the air consumption is negligible and the engine is unaffected, but the compressor delivery pressure falls rapidly with altitude and there is a corresponding wide variation in the jacking force available between sea level and 70,000 ft. In systems working against frictional or spring resistance, the jacks must be designed for the maximum altitude and, due to

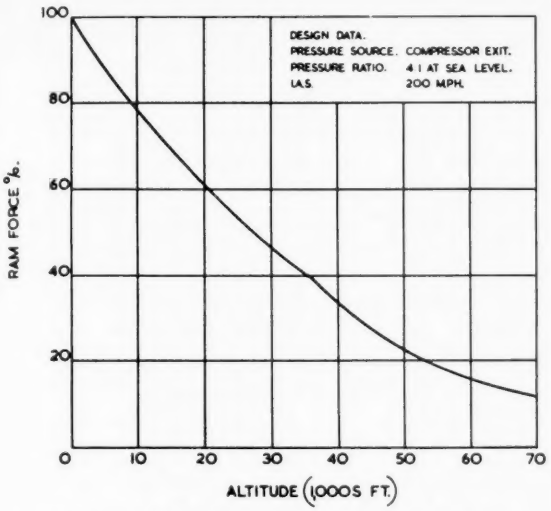


FIGURE 6. Variation of pneumatic ram force with altitude.

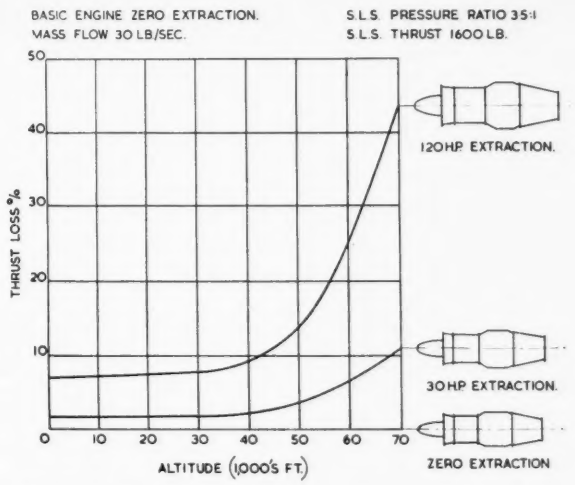


FIGURE 7. The effect of constant power extraction on engine thrust for various altitudes at 200 m.p.h. I.A.S.

the low force available, may need to be quite large. In addition, the jacking force will be sensitive to forward speed and, at high altitude, may become uncertain in operation. For this reason it is perhaps better to employ compressed air from air storage bottles when these are available or, alternatively, to compare the advantages of a hydraulic system. (*See* Fig. 6.)

When shaft power is extracted from the engine for driving aircraft accessories, it is of interest to note that, whereas the effect may not be very serious up to say 40,000 or 50,000 ft., above this it accounts for an increasingly high proportion of the net thrust and may have a significant effect on the physical size of the engine. (*See* Fig. 7.)

7. The Size of the Engine

Although in this paper the main interest, for the time being, is centred on the design of small jet engines, there obviously is a difference in size between the very small ones and those not so small; and it is of interest to examine the effect that this difference may have, both on the design layout and on the weight and performance of the engine.

In the larger sizes, say 1,000 lb. thrust and more, there will be considerable freedom of choice, both configuratively and thermodynamically, that is to say, the specific fuel consumption and the specific thrust can be allowed to exert a greater influence on the choice of pressure ratio and of axial or centrifugal layout.

With increase in size, a correspondingly higher pressure ratio can be chosen for the axial flow engine, because the high pressure blades will tend to move away from the aerodynamic and physical limitations of minimum size.

In the smaller sizes, say 300 to 800 lb. thrust, the choice will be limited, by aerodynamic and mechanical limitations, almost entirely to the centrifugal, or perhaps the mixed flow, layout. The reason is that it is usual for the performance of small axial flow compressors to deteriorate with reduction in size, because of minimum manufacturing tolerances, Reynolds number effect, and blade tip clearance effects.

It is true that some very small axial flow compressors have been built, and have given very good design point efficiencies; but it is doubtful if their performance at the higher altitudes, due to their sensitivity to critical Reynolds number effect, would equal that of the small centrifugal, quite apart from other considerations of sensitivity to fouling, damage and icing-up, of which more is said later.

For these reasons, the centrifugal or mixed flow arrangement has been the most favoured choice for the smaller engine. This choice imposes a limitation on the maximum pressure ratio of the small simple engine of about 4 : 1, with a corresponding thermodynamic limitation on the minimum specific fuel consumption of approximately 1·1, at present levels of component efficiency.

It is possible that this performance may be improved upon in the future, but the centrifugal compressor has now had many years of intensive development in the aircraft engine industry, and big improvements cannot reasonably be expected. This is not so for the turbine, and improvements in performance are most likely to come from improvements in turbine efficiency.

A higher pressure ratio, at some expense in compressor efficiency, could be obtained from a two-stage centrifugal design; but the limitations of minimum manufacturing tolerances and blade tip clearance losses mentioned for the axial flow compressor, apply also to the axial flow turbine. In consequence in a small mass flow, high pressure ratio design, the reduction in turbine size, due to the low volume flow, may produce so serious a drop in turbine efficiency that the thermodynamic advantage of the higher pressure ratio may be nullified.

For the time being, therefore, the single stage centrifugal or mixed flow compressor, in conjunction with a single stage axial flow turbine, has become,

speaking generally, the popular choice for the smaller sizes of small jet engines.

When cheapness, simplicity or expendability, are the main considerations, and specific fuel consumption relatively unimportant, the single stage centrifugal, in conjunction with the single stage radial flow turbine, should not be overlooked because the fundamental simplicity of this arrangement has much to commend it. (*See* Fig. 8.)

In the larger sizes the axial flow arrangement is more often preferred. The low frontal area and small diameter are very attractive from an installation point of view and, as the larger sizes are approached, there is the inherent advantage of higher compressor efficiency and a greater freedom of choice with regard to pressure ratio and operating temperature.

It is normal for the axial flow compressor to be driven by either a single- or a multi-stage turbine, according to the pressure and expansion ratio. With this in mind then, it will be expedient, from the point of view of both thermodynamic efficiency and specific weight, to choose a pressure ratio that is well matched to either the single- or multi-stage design. That is to say, if $3\frac{1}{2}$ or 4 : 1 is the upper limit of the compression ratio for the single stage turbine, it will be unwise to choose a pressure ratio much below this. For like reason, if a higher pressure ratio is required to improve the fuel consumption, it will be wise to avoid the intermediate pressure ratios of around 5 to 1, and go to the upper level of the compression ratio for the two stage turbine, say 7 or 8 to 1. This will produce the best compromise between specific weight and specific fuel consumption for both the single-stage and two-stage design.

There may be over-riding considerations, such as the relationship between engine weight and fuel weight for a particular flight mission, and this may affect the final choice of pressure ratio. These considerations impose a practical limitation on the choice of pressure ratio for the small axial flow engine of about 4 : 1 for the single-stage turbine, and about 7 or 8 : 1 for the two-stage design. Assuming a component efficiency of 87 per cent. for the compressor, and 87 per cent. for the turbine, there is an implied thermodynamic limitation on the minimum specific fuel consumption of approximately 1·08 for the 4 : 1 engine, and 0·87 for the 8 : 1 design, with corresponding improvements as the component efficiency levels are raised.

8. The Weight of the Engine

Before the design of a new engine progresses very far, it is usually necessary to know what the weight is going to be. In fact, this has to be guessed at long before the design is finished. When the engine is one of a family, or a variant of an existing type, it is a relatively simple matter to estimate the weight by scaling geometrically.

The performance of a gas turbine at a given flight condition, compression ratio, turbine inlet temperature and component efficiency level, is proportional to the air mass flow. Thus, if the specific weight and the

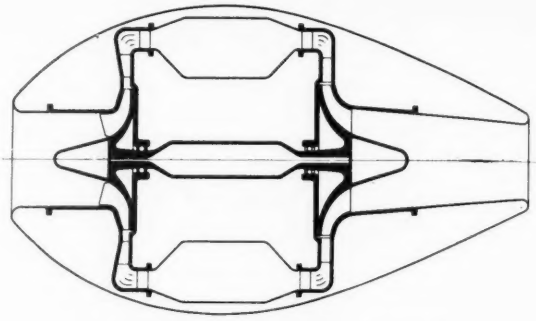


FIGURE 8. A low cost simple jet engine.

performance per unit of air mass flow is known, it is possible to estimate the change in specific weight with design air mass flow (D.A.M.F.). This can be done by scaling the engine to produce another of geometric similarity, but differing in size, weight and D.A.M.F.

The air mass flow and the weight of most of the stationary parts will be proportional to the square of the diameter, and the weight of the majority of rotating parts proportional to the cube. If an engine is scaled down geometrically, the thrust decreases as the square of the diameter, while the weight of many of the parts decreases as the cube, causing the engine weight to decrease more rapidly than the D.A.M.F.

As the smaller engine sizes are approached, however, some of the dimensions reach minimum values, and the performance per unit of air mass flow deteriorates because of such effects as minimum manufacturing tolerances, Reynolds number and blade tip clearances. For this reason, it is usual, in practice, for specific weight to decrease with the size down to a certain level. Below this, further reduction in size results in a diminishing decrease in weight with D.A.M.F., until a

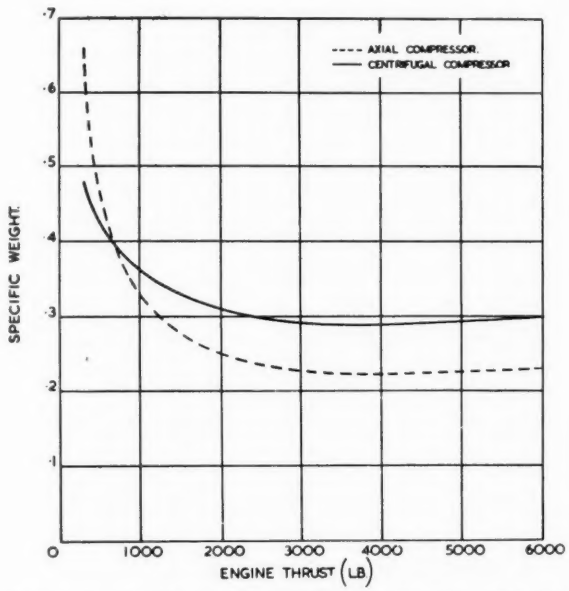


FIGURE 9. Specific net dry weight. Compression ratio 4:1. Maximum temperature 1,150°K.

critical dimension and performance level is reached, when the specific weight tends to increase again. (*See* Fig. 9.)

There are, of course, many other factors which exert a prominent influence on the specific weight of the engine. As the forward speed and the design pressure is advanced, particularly at sea level, it becomes necessary to employ thicker sections in the compressor, combustion and turbine casings, to withstand the high differential pressures. Light alloy parts may have to be changed to steel to resist the high temperatures. Higher gas bending loads on the compressor and turbine blading may require wider blade chords and, in consequence, heavier rotor discs and longer assemblies.

As the design pressure ratio is increased, more stages will be required in both the compressor and turbine. Thus, in each stage as much work of compression and expansion must be done as possible, but not at the expense of efficiency, because the fuel consumption will rise, and the additional fuel weight consumed on a particular flight may be greater than the weight saved in the engine.

Weight can be saved by cooling the turbine disc, but when cooling air is used it is wasteful of air to over-cool. Below a given temperature level, a further reduction in temperature will not allow the stress level to be raised by a useful amount. A reduction in the rim temperature of a Rex. 448 ferritic steel disc, from 600°C. to 500°C. will enable the stress level to be raised, with a consequent saving in weight on a typical turbine disc of approximately 35 per cent. (*See* Fig. 10.)

A high temperature air-cooled turbine can do much to increase the specific thrust, and reduce specific weight: but this will increase both the temperature and the velocity of the jet stream, and so reduce the propulsive efficiency. So we must ensure that what we gain on the swings we do not lose on the roundabouts; but

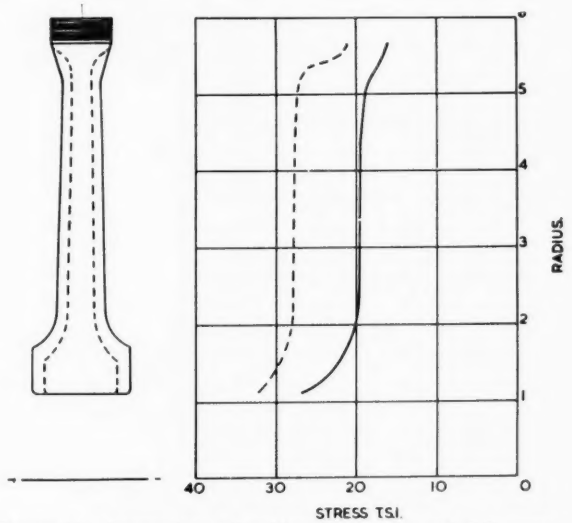


FIGURE 10. Comparison of turbine disc weight and C.F. stress for rim temperature of 500-600°C.

------ Rim temp. 500°C } Disc material ferritic steel Rex 448
——— Rim temp. 600°C } Disc weight reduction 35 per cent.

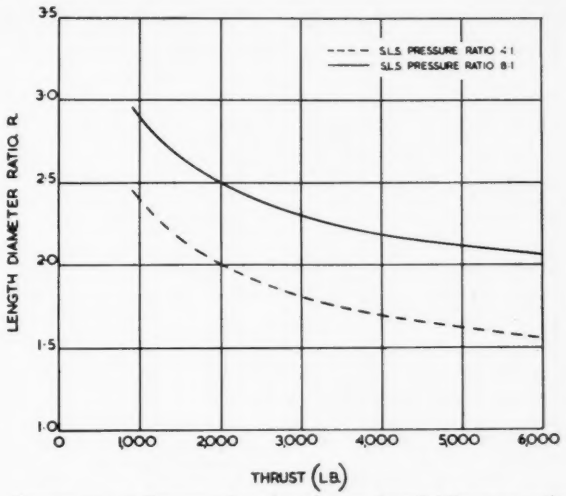


FIGURE 11. Influence of engine size on length/diameter ratio. *R* Ratio of length between front and rear bearing to compressor outside diameter.

as there are many practical difficulties to be solved before small high temperature turbines can be built, we need not worry too much just yet.

In the future it can be expected that weight will be saved by the new "Wonder Metal," titanium. One can foresee many possible uses at the cold end of the engine, particularly for the compressor rotor and blades. Estimates have shown that the weight of an axial flow jet engine may be reduced eventually by as much as 10 or 15 per cent., according to the pressure ratio, by employing titanium alloys.

9. Mechanical Design

Engines of a similar class will quite naturally differ in their detail conception and in their degree of refinement and mechanical excellence, and will show a wide difference in their specific weight, according to the quality of the mechanical design.

The weight of the engine may mean success or failure, and designing for very light weight is a specialised art quite as important as any other of the specialised procedures employed in aero engine design; this is a point which should be emphasised. The problem will differ, of course, according to whether the engine be an axial, centrifugal or mixed flow one. If it is an axial flow one, a choice will have to be made between a two- or three-bearing arrangement. Apart from any personal preference, this will depend on the length/diameter ratio, that is to say, the ratio of the length between the front and rear bearings to the compressor outside diameter, and this in turn will depend on both the compression ratio and the size of the engine.

For a given compression ratio, increase in size tends to reduce the length/diameter ratio, because certain components, such as the combustion chamber, do not lengthen proportionately with increase in size. (*See* Fig. 11.)

If the engine is a low pressure one a two-bearing design may be preferred; on the other hand, if it is a

high pressure one it may be wiser to choose a three-bearing arrangement. This can sometimes be a difficult choice to make, and sound judgment is necessary to choose between the comparative mechanical complication of the three-bearing arrangement, and the simplicity of the two-bearing layout. It must be borne in mind that deflection in the engine structure due to thermal distortion can sometimes make things very difficult in a two-bearing engine, and may mean excessive blade tip clearances at the high pressure end of the compressor to avoid fouling, with a consequent drop in compressor efficiency. It is also a matter of considerable difficulty to design a low weight two-bearing rotor.

Rotor design plays a prominent part in the weight of the axial flow engine, and it cannot be emphasised too strongly that great effort should be made to keep down the weight of the highly stressed rotor system. This can best be done by keeping down blade weight particularly at the platform and blade root fixings, because this weight is reflected in the rotor disc weight, and by effective temperature control of the turbine blade and disc assembly to permit higher stress levels to be used.

The fir-tree root fixing is still the most popular choice for the turbine blade assembly, but in the smaller engines the integral disc is now an established fact. It has been claimed that with integral blades heat can flow into the disc without interruption, thus cooling the blade at a point where fracture is most likely to occur. The problem usually is creep at the mid-span where the highest temperature normally occurs. If this condition obtains in a small engine it is doubtful if the low thermal conductivity of Nimonic 90 would allow very effective cooling of the mid-section of the blade; but if the blade chord is wide, it is possible that a reduction in mid-section temperature could be obtained

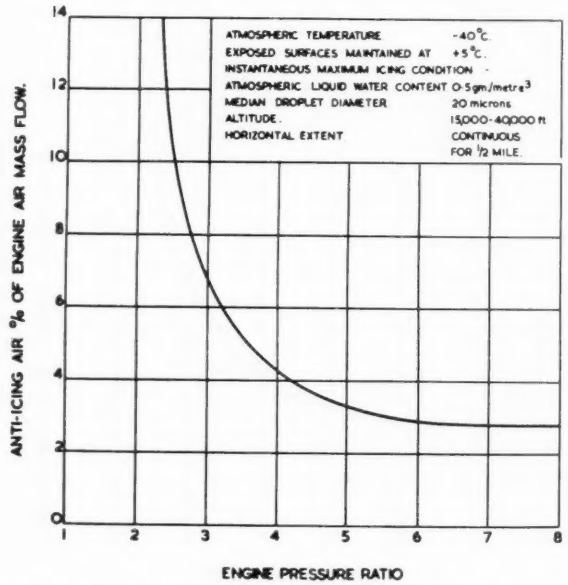


FIGURE 12. Hot air anti-icing. Variation of compressor bleed per cent. with engine design pressure ratio.

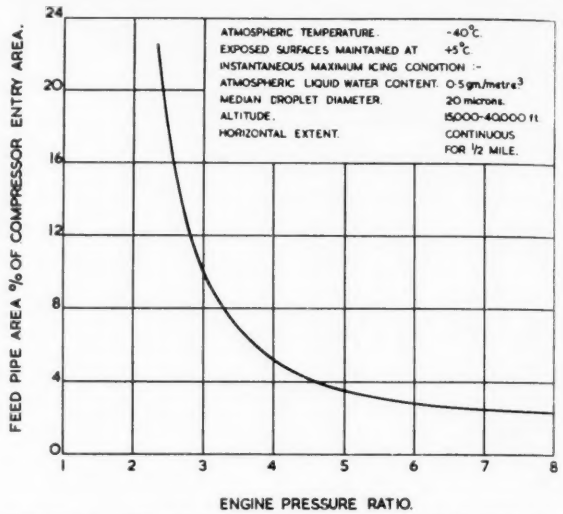


FIGURE 13. Hot air anti-icing. Variation of feed pipe area with engine design pressure ratio.

and the author would be glad to hear other views on this point.

From a weight point of view, it will be beneficial to eliminate as many parts as possible (it is surprising how many blades can be thrown away without affecting the performance) to make as many parts as possible in sheet metal, in spite of protests from the production department, and to make sure that every ounce of metal used is doing a real job of work.

In the past it has been fairly common practice to place the rotor thrust bearing at the front of the engine, and to support the turbine on a roller bearing. There is quite a lot to be said for reversing this procedure, and locating the rotor by the turbine bearing. This minimises variation in axial clearance and reduces the blade tip clearance necessary when a flaired turbine is used. Likewise balance pistons have been employed to reduce the axial load on the thrust bearings, but high-speed bearing development is now very much advanced and the author favours the elimination of the balance piston, with its troublesome labyrinth seals and high leakage loss, whenever possible, and prefers to take the difference in thrust between the compressor and the turbine, directly on the thrust bearing.

Now another word about frontal area. A lot of pressure may be put upon the designer to increase the air mass throughput of the engine by reducing the hub/tip ratio. But it will be wise not to push this process too far, too fast. In the first place it is a diminishing return, and secondly, blade vibration can be a very serious problem. Very long blades in the early blade rows may impose a serious increase in blade and disc weight to avoid vibration troubles, not to mention the delay that may arise in developing the engine to an acceptable standard of reliability. It is very doubtful if a hub/tip ratio below 0·55 is justifiable in a new design and this will leave a small margin for eventual development of the engine, when most of the other problems have been solved.

Most of the foregoing remarks apply also to the centrifugal and mixed flow engine but, speaking generally, their design is a little easier. From the start they can employ a two-bearing arrangement, the compressor, invariably, can be made throughout in light alloy with the exception of the shaft and bearings, and there will be no worry about the blades in the compressor falling off or being damaged by debris, although there may be a little trouble getting the impeller and the diffuser to work as efficiently as we should like.

10. Anti-Icing

If an engine has to operate under icing conditions, a centrifugal one will prove a happy choice, as these engines normally do not suffer very seriously from ice formation. If the air intake of the centrifugal engine is protected by a screen, particularly a forward facing one, such as might be used on a single-sided impeller, it may be necessary to anti-ice this to prevent blockage during severe atmospheric conditions. When the impeller is a double-sided one with a circumferential air intake, the problem of protecting the screen may not arise, except under very prolonged icing conditions. With regard to ice breaking away and entering the air intake, the centrifugal compressor has quite a good digestion, and apparently can swallow large quantities of ice without doing very much damage.

If an axial flow engine has been chosen there will be cause for regret when an attempt is made to protect it from ice accretion. It will be found that, under icing conditions, ice will form around the lip of the air intake over the nose bullet, along the leading edges of the support struts, and over the inlet guide vanes and, under certain conditions, over the first row rotor blades.

If the engine is not too small and the pressure ratio not much less than 5 : 1, hot air can be circulated from the compressor outlet through the inlet guide vanes, the support struts, and the nose bullet. An air circulation of approximately 3 or 4 per cent of the design air mass flow will usually give full protection to the engine, if care is taken to direct the hot air to the stagnation zones, and then to cause it to flow over the protected surfaces at high velocity, to obtain a high rate of heat transfer.

If the engine is a small one and the pressure ratio much below 5 : 1, it may not be possible to pass sufficient air through the small passage inside the inlet guide vanes due to the unfavourable mass/volume ratio, and the larger quantity required at the low compressor outlet temperature.

Figure 12 shows a typical effect of pressure ratio on the hot air required to anti-ice an axial flow engine at 0·6 of maximum r.p.m. and at −40°C., that is at let-down, through instantaneous maximum icing conditions, Fig. 13 shows the increase in feed pipe area required as the lower pressure ratios are approached.

There is little doubt that the hot gas system is now the favoured choice for anti-icing the axial flow engine. When for reasons of size and pressure ratio this is not possible, other methods have to be used and one such is the electrical system.

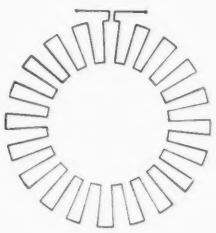
Figure 14 shows a typical electrical system; the nose bullet and the support struts are heated by resistance elements embedded in the surfaces, and the inlet guide vanes are resistance heated by connecting them in series and passing the current through them as shown in Fig. 15.

The inlet guide vanes will require a heating intensity in the region of 20/25 watts per square inch of blade surface, and the nose fairing and support struts something like 15/20 watts per square inch at the stagnation zones, shading to approximately 5 watts per square inch along the afterbodies. These are typical values and may vary according to the leading edge radii and the individual characteristics of the design.

11. Air Bleeding

It is now quite normal for a turbo-jet engine to supply compressed air for aircraft services and if this is within say, 3 or 4 per cent. of the D.A.M.F., it has little

FIGURE 15 (*above*). Electrically-heated inlet guide vanes.



Circuit diagram

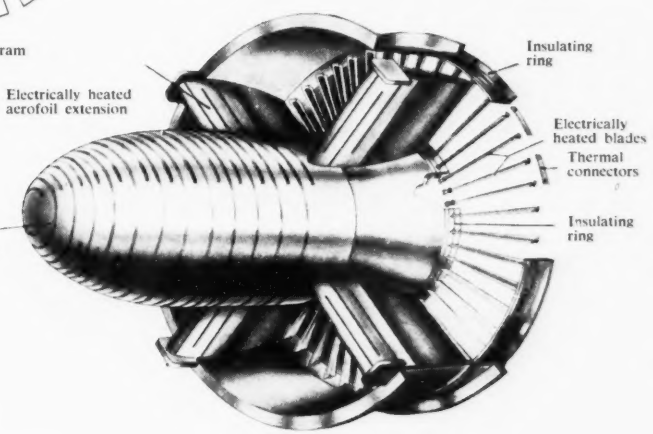


FIGURE 14 (*right*). Electric ice protection equipment.

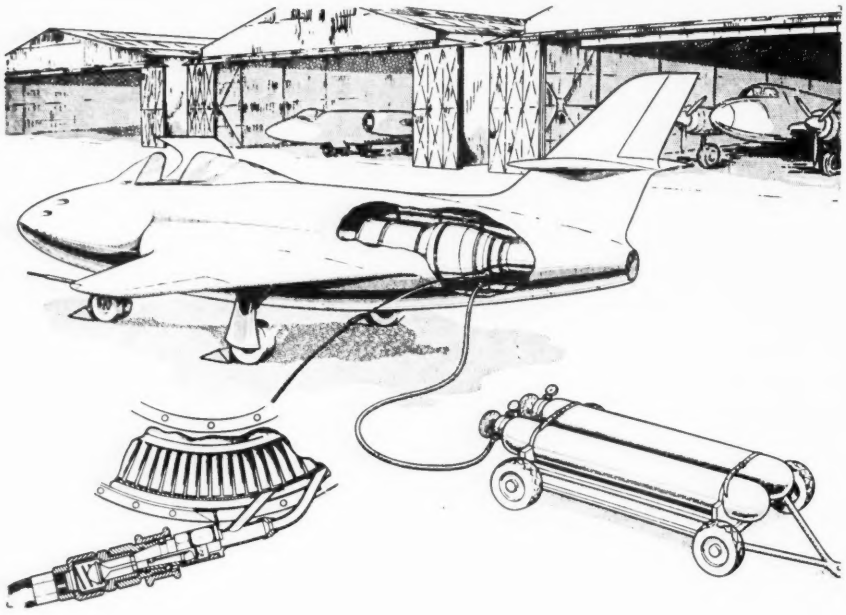


FIGURE 16. Compressed air starting (air directed on to turbine rotor blade tips).

effect on performance, or on the choice between the centrifugal and axial flow arrangement. But with recent development in aircraft lift augmentation, the engine may be required to supply up to 15 per cent. of the D.A.M.F. for this purpose during take-off and approach. It is not suggested that this requirement alone can influence the choice of engine layout, but it is of interest to compare how the centrifugal and axial flow engine react to this treatment.

At a pressure ratio of 4 : 1 and a turbine inlet temperature of 1,150° K., comparisons between typical axial and centrifugal engines, both with a 15 per cent. air bleed, have shown:—

Percentage thrust loss—centrifugal 8·6, axial 26·5
Percentage specific fuel consumption increase—centrifugal 8·6, axial 19·4
Percentage nozzle area increase—centrifugal 8·6, axial 2·6.

It would seem that all the advantages lie with the centrifugal during "take-off," when maximum thrust and maximum lift are required, and with the axial during the approach, when maximum lift and minimum thrust may be required. Both engines, of course, will require a variable area exit nozzle to obtain optimum performance.

12. Starting

All gas turbine engines have to be spun up to a relatively high rotational speed during the starting cycle and there are not many satisfactory ways of doing this for the smaller gas turbine. The most popular choice is the electric starter, which embodies a simple reduction gear and dog clutch, and which motors the engine up to the lighting-up speed and disengages at the self-sustained speed.

For the large engine, when very high starting powers are required, the cartridge and chemical turbine starters are more generally used.

An alternative to these systems which has proved very satisfactory for the Armstrong Siddeley Viper, is the direct-acting compressed-air starter. This system, which is fed from ground storage bottles, supplies compressed air, through a simple non-return valve and nozzle assembly, directly to the tips of the turbine rotor blades.

Figure 16 shows the air starting system; about 7 lb. of air at 120 lb./in.^{2} is used for each start, which takes the Viper up to idling speed in about 35 seconds.

13. Conclusion

Some of the problems have been presented that arise in the preparation of a design for a turbo-jet engine.

Many things have been discussed, and as has been seen, there are many difficult choices to make. To this end the knowledge and experience of many specialists and technicians must be co-ordinated and, whereas there are many who can grapple with the detail problems of design that may arise, there are perhaps few who have the wide knowledge and experience necessary to translate the many variables into a related form.

It is well to remember that a good engine can never be developed, it can only arise from a good and sound basic design, but when the choice has been made, let us seek to achieve the desired performance with the fewest number of parts of the most elementary geometric form.

ACKNOWLEDGMENTS

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Development of Large Intermittent Wind Tunnels

by

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SUMMARY: Two types of intermittent wind tunnel drives, the pressure storage drive (with atmospheric exhaust) and the vacuum storage drive (with atmospheric inlet), are examined and found to match well the tunnel pressure ratio-mass flow characteristics over a wide Mach number range (0 to 4). The design of components of intermittent wind tunnel installations, their operation and instrumentation are then considered in some detail. In order to increase the output of intermittent wind tunnels to a level comparable to that of continuously running tunnels, it is proposed to drive the models during each tunnel run through a range of incidence. This technique is at present under development in the National Aeronautical Establishment's High Speed Aerodynamics Laboratory and results so far obtained are discussed. Two tunnels are considered as examples of large intermittent installations: a 4 ft. square pressure-driven tunnel and a 6 ft. square vacuum-driven tunnel. The former is found to be a more compact and economical installation. Relative merits of continuous and intermittent installations are discussed.

1. Introduction

It was for reasons of power economy and design simplicity that some of the first supersonic wind tunnels, built in the late nineteen twenties in Göttingen and Aachen in Germany[1,2], were of the intermittent type. In the early thirties Ackeret pioneered the continuous high-speed wind tunnel design in Zürich, Switzerland[2,3], which was followed by a large continuous installation in Guidonia, Italy[2]. Following these early developments most high-speed wind tunnels built outside Germany were of the continuous or at least long duration type, whereas supersonic research in Germany was conducted, until 1945, mainly in intermittent wind tunnels, in which the first supersonic missiles, including the A-4 rocket, were developed. After the war, the expansion of high-speed wind tunnel facilities was greatly accelerated and large, continuous installations have since been completed or are being constructed in the United States, United Kingdom and elsewhere. Without going into details of engineering complexity of continuous-flow high-speed wind tunnels at this stage, one can state that the drive (comprising motors, compressors and coolers) forms the major part of such installations, both as regards cost and design effort.

It was with a view to reducing the amount of specialised design and cost that, in the countries with more limited resources, the intermittent wind tunnel drive was recently considered for large wind tunnels. The German experience in intermittent tunnel design and operation did not go beyond the 16-in. square working section size[1] and conventional model testing techniques were used, the model attitude being kept constant during each tunnel run. Recent advances, particularly in the field of instrumentation, make it possible to obtain without undue difficulty pressure and force readings in a matter of a fraction of a second, and to cover, during a single tunnel run (of the order of 15 sec. duration), a range of model attitudes. With the development of such high-speed testing techniques the output of an intermittent wind tunnel installation becomes comparable to that of a conventional continuous one, while the engineering complexity of components extraneous to the wind tunnel duct proper (from entry contraction to diffuser exit) is eliminated. Moreover, from the point of view of operating convenience, an intermittent installation offers many advantages over a continuously running one, at least for carrying out most types of aerodynamic tests.

In the evaluation of operating and design problems of large intermittent wind tunnel installations, use will be made of experience gained with the existing smaller discontinuous tunnels. In particular, the data obtained from the N.A.E. (Canada) 30 × 16 in. high-speed intermittent wind tunnel, believed to be one of the larger in size while having a maximum running time of only 15 seconds, will be utilised.

In addition to design data applicable to intermittent tunnel installations, the relative merits of large continuous and intermittent tunnel types will be discussed.

Notation

A	tunnel working cross-sectional area (ft.^{2})
A_d	diffuser throat area (ft.^{2})
$a_0 = a_{0i}$	velocity of sound in the storage vessel at the start of tunnel run and at tunnel stagnation conditions (ft./sec.)
C_D	model drag coefficient, based on model area S

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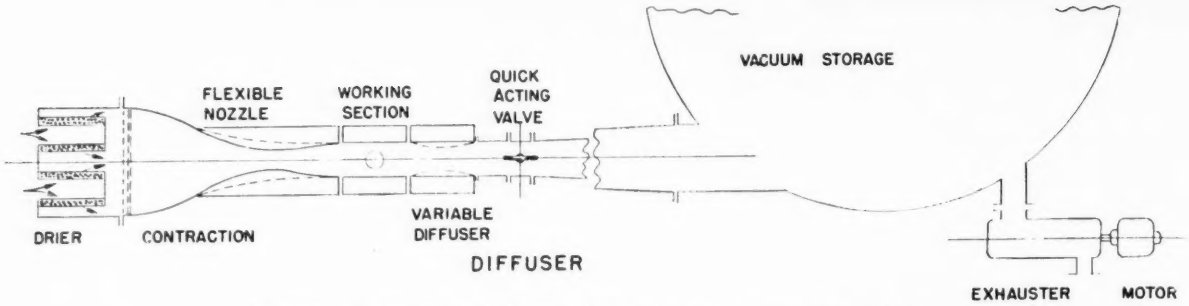

FIGURE 1. Intermittent wind tunnel installation with vacuum storage drive.

D model drag (lb.)
J mechanical equivalent of heat = 1,400 ft. lb./C.H.U.
$l/2$ maximum radius, *e.g.* half of model length
M working section Mach number
P pressure (lb./in.^{2} abs.)
P' pressure in storage vessel
P_0 tunnel stagnation pressure and pressure in the storage vessel at the end of run = constant
P_i initial storage pressure
P_{0i} pressure in the storage vessel at the start of tunnel run
P_{0i}' increased storage pressure
Q volume flow at the compressor intake
Q^* volume flow at tunnel sonic speed
S model area (ft.^{2})
s entropy (C.H.U./(lb.°K.))
T temperature of air after throttling (°K.)
T' air temperature in storage vessel
T_0 constant stagnation temperature equal to the initial storage temperature
T_∞ free stream (static) temperature
t running time (sec.)
t_v running time of a vacuum storage wind tunnel
t_p running time of a pressure storage wind tunnel
V storage capacity (ft.^{3})
V' increased storage volume
v_∞ free stream velocity (ft./sec.)
W weight of air (lb.) discharged from storage; or tunnel air flow (lb./sec.)
γ ratio of the specific heats = $C_p/C_v = 1{\cdot}4$ for air
ψ nozzle expansion ratio = A^*/A
μ experimental factor (*see* p. 265)
ω angular velocity (sec.$^{-1}$)

Asterisks refer to conditions at the tunnel throat.

2. Main Components of Intermittent Wind Tunnel Installations

The speed range of intermittent wind tunnels here considered extends from low subsonic speeds to high supersonic velocities, of the order of Mach number 4·5, but does not reach into the hypersonic range.

The upper limit of this speed range stems from consideration of two factors. First, it corresponds to the maximum Mach number attainable at normal air stagnation temperatures and with practical pressure levels. Secondly, it corresponds to about as wide a speed range as can be covered with a single, variable Mach number (flexible plate type) nozzle.

With air at normal stagnation temperature, drying to a low moisture content, of the order of 0·0001, is required to avoid condensation effects in the nozzle or working section. With large tunnel flows it seems impracticable to store* and recirculate dry air required for each tunnel run and therefore the tunnel installation is of the open-circuit type and includes a drier.

As regards wind tunnel drive, two types appear practicable for large intermittent tunnels, both of the direct-drive type: (1) the *vacuum storage drive* and (2) the *pressure storage drive*.

In the first system, Fig. 1, atmospheric air passes during a tunnel run through a drier and wind tunnel duct into a vacuum vessel which is continuously evacuated to the atmosphere. This is the original high-speed tunnel drive first introduced by Prandtl some 25 years ago.

The installation employing a *pressure storage drive*, Fig. 2, consists of a vessel in which dry air required for a tunnel run is stored under relatively high pressure. It then passes through a throttle valve and a heater, which maintain constant pressure and temperature in the tunnel working section, and exhausts from the tunnel diffuser into the atmosphere. With the heater located downstream of the throttle valve, the amount of heat required to maintain constant temperature is much smaller than if the air in the storage vessel were heated, and the Joule-Thomson temperature drop due to throttling can be made good. So located, the heater serves also to damp out flow fluctuations set up by the constant pressure throttle valve.

Alternatively, a substantially isothermal expansion can be obtained by filling the storage vessel with a matrix, which occupies a small volume and may consist, for example, of randomly distributed metal cans. This appears to be an economical and mechanically simple method of temperature stabilisation which results, moreover, in a longer running time than when the heater is located downstream of the throttle valve.

*The required storage volume is estimated in Section 3.8, page 268.

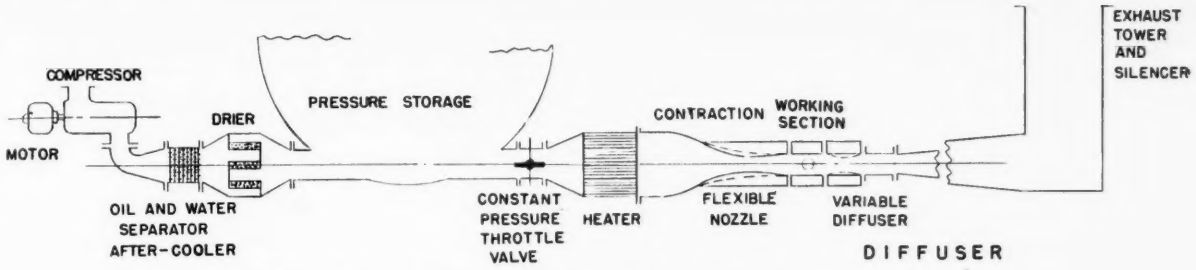

FIGURE 2. Intermittent wind tunnel installation with pressure storage drive.

3. Intermittent Tunnel Drive

3.1. MATCHING OF TUNNEL AND DRIVE CHARACTERISTICS

With continuous wind tunnels the problem of matching compressor and tunnel volume flow and pressure ratio characteristics presents a major difficulty, particularly if a wide Mach number range is to be covered in a single tunnel duct. Typical* volume flow-pressure ratio requirements of a wind tunnel are shown in Fig. 3 for Mach numbers from 0 to 4, in terms of volume flow Q at the compressor intake relative to volume flow at tunnel sonic speed, Q^*. They are in general incompatible with the characteristics of efficient axial† flow compressors, due to excessive flow range at subsonic speeds and large variations in both pressure ratio and volume flow at supersonic speeds. Unless special steps were taken, a compressor would operate at a low efficiency over most of the Mach number range, the tunnel Reynolds number being accordingly reduced.

In practice, the compressor-wind tunnel matching problem can be overcome, over discrete speed intervals, in a number of ways, none of which are simple or cheap. They range from special variable blade pitch compressors, compressors with free-wheeling, feathering or removable stages, to arrangements involving complications in the tunnel circuit layout, such as extra compressors located in additional circuit legs, working section by-pass-diffuser injector systems, separate tunnel circuits of different sizes coupled to the same compressor, variable size tunnel working sections, and so on. It is interesting to note that the above difficulties were encountered in the first continuous supersonic wind tunnel design and that a working section by-pass was then utilised by Ackeret[3].

In spite of incorporation of one or more of the above matching artifices, the Mach number span of a continuous wind tunnel is usually small and does not extend from low subsonic velocities to high supersonic ones. This speed range is however easily covered by an intermittent drive, as will be shown by determining the tunnel pressure ratio for a constant running time with a given storage capacity and tunnel size over the Mach number range and comparing it with actual required minimum tunnel pressure ratio. Moreover, an intermittent drive utilises only standard industrial machines and does not require any modifications of the tunnel circuit.

The required minimum tunnel pressure ratio, as assumed on the basis of experimental data, is given in Fig. 4, curve *a*, and Table I.

The above values are conservative for tunnels with ventilated working sections in the transonic range and at higher Mach numbers, for constant geometry diffusers at $M<2{\cdot}5$ and for variable geometry diffusers at $M>2{\cdot}5$[5]. Comparison with the variable diffuser data at $M>2{\cdot}5$ is appropriate for intermittent tunnels, in which a variable second throat is required also for subsonic speed control and larger than required pressure ratio is available at starting.

At Mach numbers $M\leqslant 1$, a constant pressure ratio of 1·2 is assumed. This relatively high value is appropriate due to the use of a sonic diffuser choke to control subsonic Mach number in intermittent wind tunnels.

In general, the assumed pressure recovery is considered conservative at all Mach numbers, even if account is taken of the extra losses introduced by the model and its support, the quick-acting valves and ducting. This is confirmed by the breakdown pressure

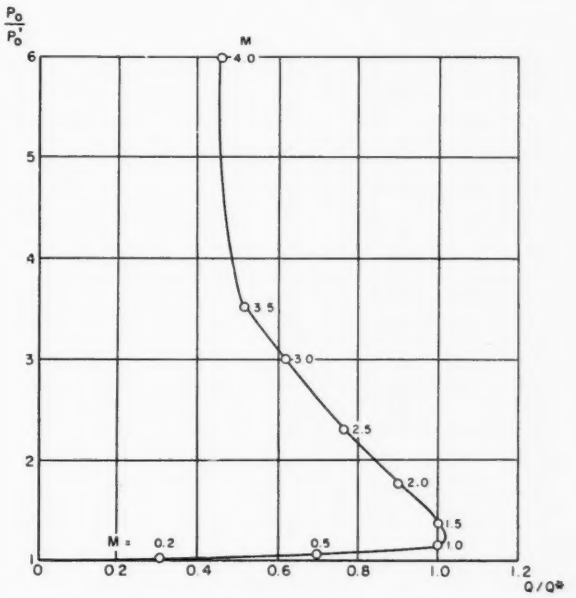

FIGURE 3. Pressure ratio and compressor intake volume flow (based on Table I and curve *a'—a*, Fig. 4).

*Based on pressure ratio given by curve *a'—a*, Fig. 5.

†In view of large power consumption of continuous tunnels, more efficient axial compressors are preferred to centrifugal ones. Also, they make a better installation in the tunnel circuit.

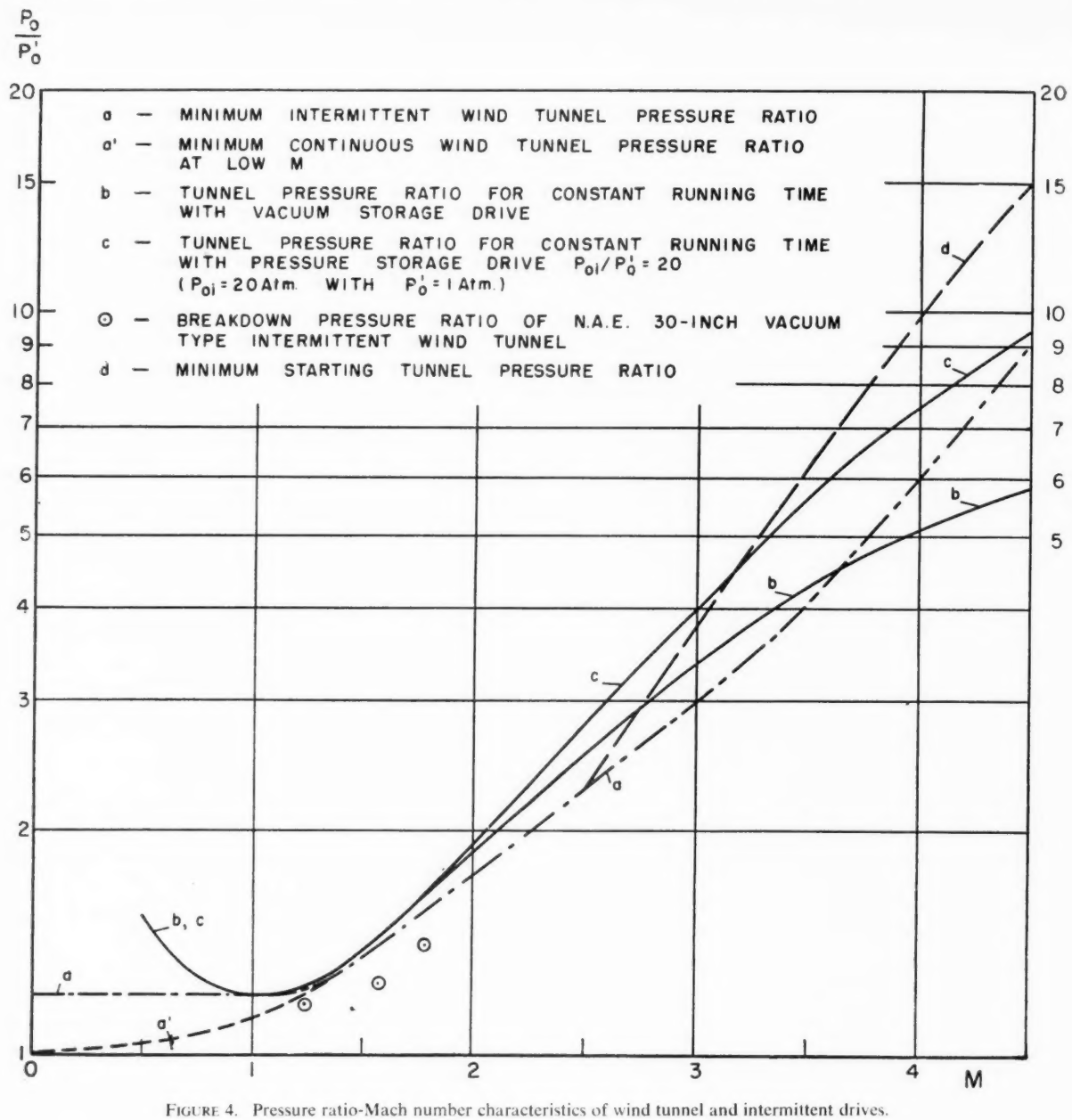

FIGURE 4. Pressure ratio-Mach number characteristics of wind tunnel and intermittent drives.

ratios measured in the N.A.E. 30-inch wind tunnel at low supersonic Mach numbers and shown in Fig. 4.

In Table I and Fig. 4, curve *d*, are also included minimum values of wind tunnel pressure ratio required for starting of supersonic flow in the working section. As before, they are conservative and correspond to realistic conditions of tunnel testing. The starting pressure ratio values are applicable to operation of pressure storage driven tunnels, which, unlike the vacuum driven ones, run at an essentially constant pressure ratio. With the former type the pressure ratio available at starting is always very large and therefore the starting requirements need not be taken into account.

We can now consider the running time t_r of a *vacuum storage driven* wind tunnel, given by (Ref. 3).

$$t_r = \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{V}{\mu a_0 \psi A}\left(\frac{P_0'}{P_0} - \frac{P_1}{P_0}\right) \text{sec.} \qquad (1)$$

$$= 1{\cdot}728 \frac{V}{\mu a_0 \psi A}\left(\frac{P_0'}{P_0} - \frac{P_1}{P_0}\right) \text{sec. for } \gamma = 1{\cdot}4$$

where $\psi = A^*/A$

$$= M\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{-\frac{\gamma+1}{2(\gamma-1)}} \qquad (2)$$

and μ is an experimental factor.

TABLE I

MINIMUM REQUIRED TUNNEL PRESSURE RATIO

M	$\leqslant 1{\cdot}2$	1·5	2·0	2·5	3·0	3·5	4·0	4·5
P_0/P_0' (Running)	1·2	1·35	1·75	2·3	3·0	4·0	6·0	9·0
P_0/P_0' (Starting)	1·2	1·35	1·75	2·3	3·8	6·2	10·0	15·0

For t_v to be constant the tunnel pressure ratio is given by

$$\frac{P_0'}{P_0} = \lambda_v M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}} + \frac{P_1}{P_0} \qquad (3)$$

where $$\lambda_v = t_v \mu a_0 A / V = \text{constant}. \qquad (4)$$

A suitable value has now to be chosen for P_1/P_0. Since, except at high Mach numbers, $P_1/P_0 << P_0'/P_0$, the choice is not critical over most of the Mach number range. From considerations of typical exhauster characteristics and tunnel performance, $P_1 = 100$ mm. Hg abs. (2 lb./in.^{2} absolute) appears suitable, giving $P_1/P_0 = 0{\cdot}132$ with $P_0 = 760$ mm. Hg abs.

It is convenient to investigate the required pressure ratio in relation to the running time t_v* at sonic speed. We thus obtain from equation (3), the expression

$$\frac{P_0'}{P_0} = 1{\cdot}21M\,(1 + 0{\cdot}2M^2)^{-3} + 0{\cdot}132 \qquad (5)$$

for the pressure ratio with which the running time at any Mach number is equal to that at sonic speed.

Values of P_0/P_0' so found are shown in Fig. 4, curve *b* and Table II. The agreement with the actually required tunnel pressure ratio is excellent over practically the whole supersonic speed range ($M \leqslant 4$) and indicates that the *vacuum storage drive is well matched* to the *high-speed tunnel characteristics*. This is also evident from the consideration of the running time available with the assumed (Fig. 4, curve *a*) tunnel pressure ratio in relation to its value at sonic speed. The ratio t/t^* is given in Fig. 5, curve *a* and Table II. The running time is practically constant (within about 15 per cent.) in the range $M = 0{\cdot}8$ to $M = 2$ and increases at lower and higher (up to $M = 3{\cdot}75$) speeds.

The decrease of the running time at $M > 3{\cdot}75$ is due to the assumed relatively high initial storage pressure of 100 mm. Hg. In order to operate at Mach numbers up to $M = 4{\cdot}5$, the running time and minimum pressure ratio requirements necessitate evacuation to a lower pressure. At Mach numbers of 4 and 4·5 initial storage pressures of 75 mm. Hg and 50 mm. Hg respectively will give a running time equal to that available at sonic speed.

TABLE II

CHARACTERISTICS OF VACUUM STORAGE DRIVE

M	0·5	1·0	1·5	2·0	2·5	3·0	3·5	4·0	4·5
P_0/P_0' for $t_v = t_v$* with $P_1/P_0 = 0{\cdot}132$	1·53	1·20	1·37	1·86	2·52	3·37	4·24	5·04	5·73
t/t^*	1·34	1·0	1·017	1·05	1·14	1·21	1·14	0·52	—

A similar analysis is required to assess the suitability of the *pressure storage drive system*, sketched in Fig. 2. During a tunnel run high pressure air flows from storage vessel through a quick-acting, constant pressure throttle valve and a heater into the tunnel entry contraction and is eventually exhausted to the atmosphere. The heater maintains an approximately constant stagnation temperature, which would otherwise decrease appreciably due to expansion of air in the storage vessel. The running time t_p obtainable with this system is easily determined from consideration of volume of air available for each tunnel run at the tunnel stagnation conditions. This is given by

$$V \frac{P_{0i}}{P_0} - V \left(\frac{P_{0i}}{P_0}\right)^{\frac{\gamma-1}{\gamma}} \qquad (6)$$

The first term represents the initial equivalent storage volume at pressure P_0, while the second one equals the residual volume corrected for isentropic expansion in the vessel. We can now write

$$\rho_0 V \left[\frac{P_{0i}}{P_0} - \left(\frac{P_{0i}}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right] = A^* \rho^* a^* t_p. \qquad (7)$$

In terms of stagnation parameters this gives

$$t_p = \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{V}{A a_{0i} \psi} \left[\frac{P_{0i}}{P_0} - \left(\frac{P_{0i}}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right]. \qquad (8)$$

In order to investigate the pressure storage drive performance in relation to tunnel characteristics, a value of the storage pressure must be chosen. As pointed out in Section 6, there appears to be no advantage in using very high storage pressures of the order of 2,000 to 4,000 lb./in.^{2} abs. Instead, it is suggested that a "safe minimum" storage pressure, sufficient to cover the whole Mach number range available in one tunnel duct running at normal stagnation temperature, should be selected. On this basis a value of 20 atm. (or 300 lb./in.^{2} abs. approximately), somewhat larger than the minimum 15 atm. required for starting at $M = 4{\cdot}5$ (Table I and Fig. 4, curve *d*), was taken.

In Table III and Fig. 4, curve *c*, the tunnel pressure ratio is shown which, with a constant storage pressure of 20 atm. and atmospheric exhaust, would give, at all Mach numbers, the same running time as at sonic speed with $P_0/P_0' = 1{\cdot}2$. Comparison with the minimum required tunnel pressure ratio, Fig. 4, curve *a*, indicates a close agreement over the whole Mach number range and possibility of operating the tunnel at larger than the minimum stagnation pressures at Mach numbers from 2 to 4·5. Alternatively, longer running times are obtained when running at the minimum stagnation pressures, as indicated in Table III and Fig. 6, curve *b*.

We have thus been able to show that the direct intermittent tunnel drives of the vacuum and pressure storage type are *well matched to the tunnel requirements over the whole Mach number range*. In effect, owing to the presence of residual gas in the vacuum and pressure storage vessels at the end of a tunnel run, these drives have the variable volume characteristics required

TABLE III

CHARACTERISTICS OF PRESSURE STORAGE DRIVE

M	0·5	1·0	1·5	2·0	2·5	3·0	3·5	4·0	4·5
P_0/P_0' for $t=t^*$ $P_{0i}=20$ atm. $P_0'=1$ atm. $P_0/P_0'=1{\cdot}2$ at $M=1$	1·55	1·2	1·4	1·9	2·8	4·0	5·6	7·4	9·5
t/t^* for $P_{0i}=20$ atm. $P_0'=1$ atm. and assumed P_0/P_0' (Table I)	1·34	1·0	1·03	1·1	1·27	1·45	1·6	1·43	1·1

at supersonic speeds by a tunnel and indicated in Fig. 3. At lower subsonic speeds considerably larger running times are possible but no inefficiency results from this lack of matching; on the contrary, the duration or frequency of the runs, and therefore the tunnel output, can be increased, or, in the case of the pressure storage drive, a higher model Reynolds number can be obtained.

3.2. DURATION OF TUNNEL RUNS

The actual duration of tunnel runs is best calculated at any Mach number from Tables II and III or Fig. 5 provided the running time t^* at sonic speed is known. From equations (1) and (8) we obtain, for the two types of tunnel drive:

$$\frac{t_v^* A a_0}{V} = \frac{1{\cdot}21}{\mu} \quad . \quad . \quad . \quad (9)$$

for the vacuum storage drive (with $P_1/P_0=0{\cdot}132$)

and

$$\frac{t_p^* A a_{0i}}{V} = 25 \quad . \quad . \quad . \quad (10)$$

for the pressure storage drive (with $P_{0i}/P_0'=20$, $P_0/P_0'=1{\cdot}2$).

In the former case, the question of the value of μ arises. Theoretically, $\mu=\gamma$ if adiabatic conditions are assumed (*i.e.* no heat flow from tunnel air to storage vessel and atmosphere during tunnel run), or $\mu=1$ for isothermal compression in the storage vessel. In practice, factor μ, as determined experimentally from observed t_v, P_0'/P_0 and P_1/P_0, lies between these two theoretical extremes, its value depending on the relative sizes of storage capacity and tunnel working section. In general, μ can be expected to increase with increase in the storage volume due to the square/cube law. Values of μ as determined from the N.A.E. intermittent tunnels are given in Table IV.

As would be expected, μ approaches the isothermal value of one in the case of the small tunnel but is considerably higher for the larger one. In view of the larger storage capacities considered here, a value of $\mu=1{\cdot}15$ will be taken. It is larger than that appropriate to the 10-inch tunnel, but smaller than that obtained with the very short running times.

Putting $\mu=1{\cdot}15$, a vacuum capacity of 1,063 ft.^{3} is required for a one second run with a 1 ft.^{2} tunnel working section at sonic speed.

With the pressure storage drive, a figure of 45 ft.^{3}/(ft.^{2} sec.) is obtained, with $a_0=1{,}118$ ft./sec. ($T_0=20°$C.) in both cases.

3.3. *FREQUENCY OF TUNNEL RUNS AND POWER REQUIREMENTS

To complete the examination of drive suitability we will now consider the frequency of tunnel runs and power requirements.

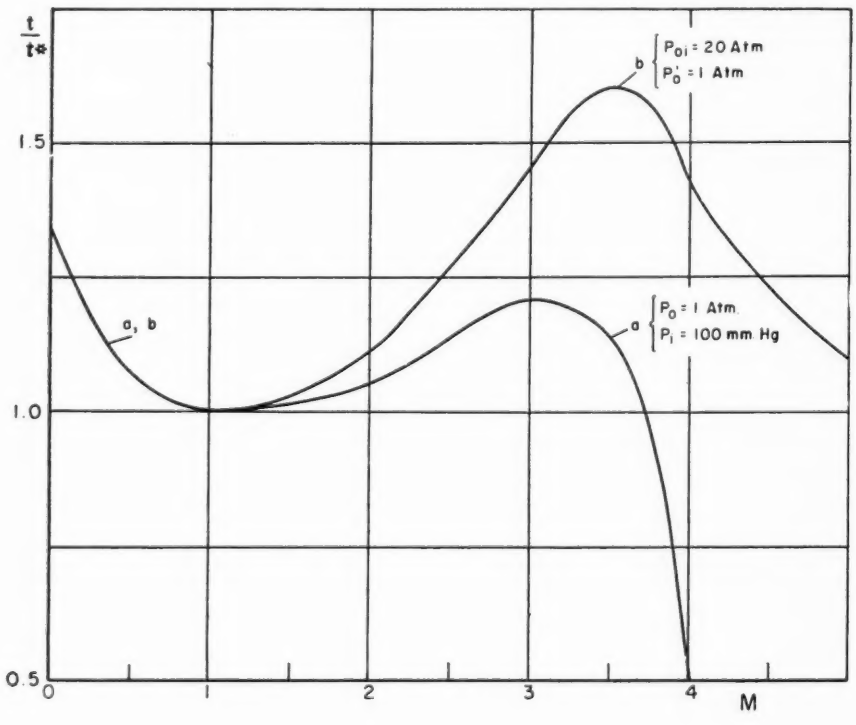

FIGURE 5. Variation of tunnel running time with vacuum (curve *a*) and pressure (curve *b*) storage drive.

TABLE IV

EXPERIMENTAL VALUES OF FACTOR μ
Storage capacity: 35 ft. diam. sphere, 22,500 ft.^{3}

Mach number	*Tunnel working section*	*Duration of tunnel run*	μ
1·4 to 2·0	10 × 10 in.^{2}	30 sec.	1·1
1·0 to 1·6	30 × 16 in.^{2}	6 sec.	1·20 to 1·24

From Tables II and III and Fig. 4 it is evident that, for a constant running time, the maximum quantity of air is used up in a single run at tunnel sonic speed, with both types of drive. This follows from the fact that the storage vessel has to be evacuated from the highest pressure or pressurised from the lowest one for tunnel runs at sonic speed, so that the frequency of runs is then smallest. The compressor plant should therefore be designed for this minimum frequency condition.

Typical variation of run frequency f with Mach number is shown in Fig. 6 for vacuum and pressure storage installations in relation to the frequency f^* at $M = 1$ and for a constant running time at all speeds. It is seen that the output of the tunnel is doubled at high Mach numbers.

As regards power requirements, they depend on the type of machines chosen and only approximate figures can be quoted here. For vacuum storage operation, about 1,500 h.p. are required to evacuate a 10^5 ft.^{3}-vessel from atmospheric to 100 mm. Hg pressure in 10 minutes. With the pressure storage system, about 8,000 h.p. are needed to charge a vessel of 10^4 ft.^{3}-capacity to 20 atm. in 10 minutes.

3.4. STORAGE OF AIR

Air storage vessels of the type required for operation of intermittent wind tunnels are currently used in industry and their design and manufacture do not depart from standard engineering practice. Most of the existing intermittent tunnel installations utilise for vacuum storage spherical, welded steel vessels, which have been built up to some 200,000 ft.^{3}-capacity (or 74-ft. diam.)

For constant stress in thin-walled, spherical vessels, the ratio of diameter to wall thickness should remain constant and a value of about 670 has been currently used for vacuum spheres.

With pressure storage drive, spherical or cylindrical vessels can be used for pressures of the order of 20 atm. The choice of the vessel geometry would be mainly influenced by economic considerations, including the erection costs.

3.5. QUICK-ACTING VALVES

This is another component of intermittent wind tunnel installation which is commercially available. There are several makes of butterfly-type, rubber-lined valves driven by compressed air cylinders, in sizes ranging up to 9 ft. in diameter. Although butterfly valves are aerodynamically worse than the plug type ones, they are much cheaper and their performance in other respects is completely satisfactory. In any case the pressure losses caused by the butterfly are not too serious in an intermittent tunnel installation with which large pressure ratios are available.

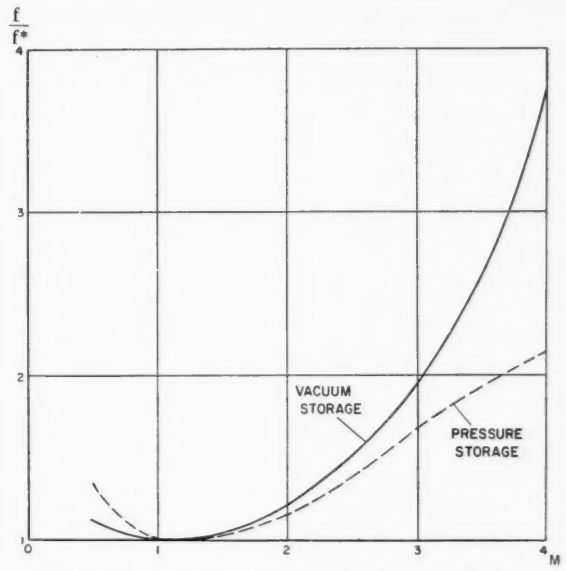

FIGURE 6. Frequency of tunnel runs of constant duration.

In the N.A.E. 30-inch high-speed wind tunnel a 2·5-ft. diam., rubber-lined, butterfly valve has been in use for over a year and no deterioration was noticed after 2,000 cycles. With this valve a pressure of about 3 mm. Hg. abs. is obtainable in the sphere, indicating the excellence of the rubber seal.

An important factor in the performance of valves used with intermittent wind tunnels is the time taken to open and close. From tests made with the above-mentioned valve, the results of which are shown in Fig. 7, it was found that the butterfly movement was independent of tunnel flow and that the valve opened in about 0·7 sec. To avoid compression waves of large

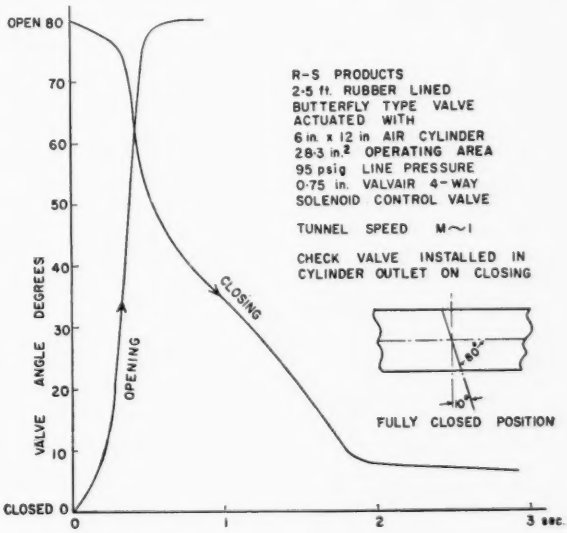

FIGURE 7. Time of closing and opening of butterfly valve.

amplitude on valve closing, which may cause damage to the tunnel structure, the closing time of this valve was increased to about 2 sec. (Fig. 7) by inserting a check valve in the compressed air exhaust line.

To avoid excessive losses, the butterfly valves must be sufficiently large to be located in low Mach number flow. With the vacuum drive, a nominal* valve area of twice the tunnel working section area, corresponding to 0·3 Mach number at tunnel sonic speed, can be safely taken. In fact, the pressure recovery of the N.A.E. 30-inch wind tunnel (Fig. 4) would indicate that a much smaller valve area, only half as large again as the working section area, can be used.

In the case of pressure-driven tunnels, the maximum required throttle valve area is somewhat smaller due to temperature drop in the storage vessel. With 20 atm. driving pressure, this reduction amounts to 50 per cent. (at equal Mach numbers at the valve).

3.6. HEATING REQUIREMENTS OF PRESSURE STORAGE DRIVE

With the pressure storage drive, in order to ensure a constant Reynolds number throughout the duration of a tunnel run, the air has to be heated before entering tunnel working section. If this were not done, the Reynolds number increase during a run would be appreciable and equal to (assuming viscosity$\propto T^k$, $k=0{\cdot}8$)

$$R_2/R_1=(P_{01}/P_0)^{\frac{\gamma-1}{\gamma}(k+\frac{1}{2})}$$

$$=(P_{01}/P_0)^{0{\cdot}37} \quad . \quad . \quad (11)$$

which, at sonic speed, gives, with $P_{0i}=20$ atm. and $P_0=1{\cdot}2$ atm., $R_2/R_1=2$.

Although an increase in Reynolds number of this order might be considered desirable, in practice it would be objectionable for a number of reasons. For example, the Reynolds number could not be allowed to vary if a range of model attitudes were to be covered in a single tunnel run. Also, the Reynolds number variation could cause changes in the value and distribution of Mach number in the working section.

The amount of heat which has to be supplied to the tunnel air in order to maintain a constant stagnation temperature is given by:

$$H=\int_0^W C_p(T_0-T)\,dW. \quad . \quad . \quad (12)$$

The temperature drop (T_0-T) in equation (12) is due to (*i*) isentropic expansion of air in the storage vessel and (*ii*) the Joule-Thomson cooling effect in throttling. Denoting by T', P' the air temperature and pressure in the storage vessel, we have accordingly

$$W=Vg\rho_{01}\left[1-\left(\frac{T'}{T_0}\right)^{\frac{1}{\gamma-1}}\right] \quad . \quad . \quad (13)$$

*Includes butterfly blockage.

TABLE V

HEATING REQUIREMENTS OF PRESSURE STORAGE DRIVE

M	1·0	1·5	2	3	4
P_{0i}/P_0	16·67	14·8	11·4	6·67	3·33
HJ/VP_{0i}	0·68	0·66	0·61	0·47	0·28

$P_{0i}=20$ atm., $P_0'=1$ atm., P_0/P_0' as given in Table I.

and $$T'-T=n(P'-P_0)\left(\frac{273}{T'}\right)^2 \text{°C.} \quad . \quad (14)^*$$

with $$n=0{\cdot}0189\text{°C. in.}^2\text{/lb. for air.}$$

Integration of equation (12) yields, in terms of pressure ratio

$$\frac{HJ}{VP_{0i}}=\frac{\gamma}{\gamma-1}\left\{1-\left(\frac{P_0}{P_{0i}}\right)^{\frac{1}{\gamma}}-\frac{1}{\gamma}\left(1-\frac{P_0}{P_{0i}}\right)+\right.$$

$$+\frac{n}{T_0}\left(\frac{273}{T_0}\right)^2\left[\frac{1}{3-\gamma}P_{0i}\left[1-\left(\frac{P_0}{P_{0i}}\right)^{\frac{3-\gamma}{\gamma}}\right]-\right.$$

$$\left.\left.-\frac{1}{3-2\gamma}P_0\left[1-\left(\frac{P_0}{P_{0i}}\right)^{\frac{3-2\gamma}{\gamma}}\right]\right]\right\}. \quad (15)$$

The terms in the first line account for cooling due to isentropic expansion of air in the vessel. For large pressure ratios P_{0i}/P_0 they reduce to unity. The upper limit of the heat quantity required in the absence of the Joule-Thomson effect is thus equal to VP_{0i}/J.

Similarly, the upper limit of the heat quantity required because of the Joule-Thomson cooling is given by

$$\frac{HJ}{VP_{0i}}=\frac{\gamma}{(\gamma-1)(3-\gamma)}\frac{n}{T_0}\left(\frac{273}{T_0}\right)^2P_{0i} \quad . \quad (16)$$

For moderate storage pressures P_{0i} the Joule-Thomson effect can be neglected in estimating the heating requirements. The values of HJ/VP_{0i}, excluding the Joule-Thomson effect, were calculated for a number of pressure ratios P_0/P_{0i}, which correspond to Mach numbers given in Table I and $P_{0i}=20$ atm., with P_0/P_0' for the actual tunnel, Table I and atmospheric exhaust pressure. From Table V and Fig. 8 it is seen that the maximum amount of heat has to be supplied at sonic speed. Using the figure of 45 ft.^{3}/(ft.^{2} sec.) for storage capacity (*see* p. 264), we find that 930 C.H.U. have to be supplied per second of running time per square foot of tunnel working section area at tunnel sonic speed.

The rate at which air must be heated increases during a tunnel run and becomes very large at the end of the run. At $M=1$, it reaches 2,300 C.H.U./sec. per square foot of tunnel working section area. For this reason, heating systems employing energy storage and therefore analogous to the tunnel drive system, rather than direct heating by fuel combustion or electricity, appear suitable. In practice, a regenerative type of heat exchanger could be used, of a mass sufficient for the drop in temperature of the tunnel air to be negligible. The theoretical design of the heat exchanger is a matter

*As given by Schüle[15], p. 452.

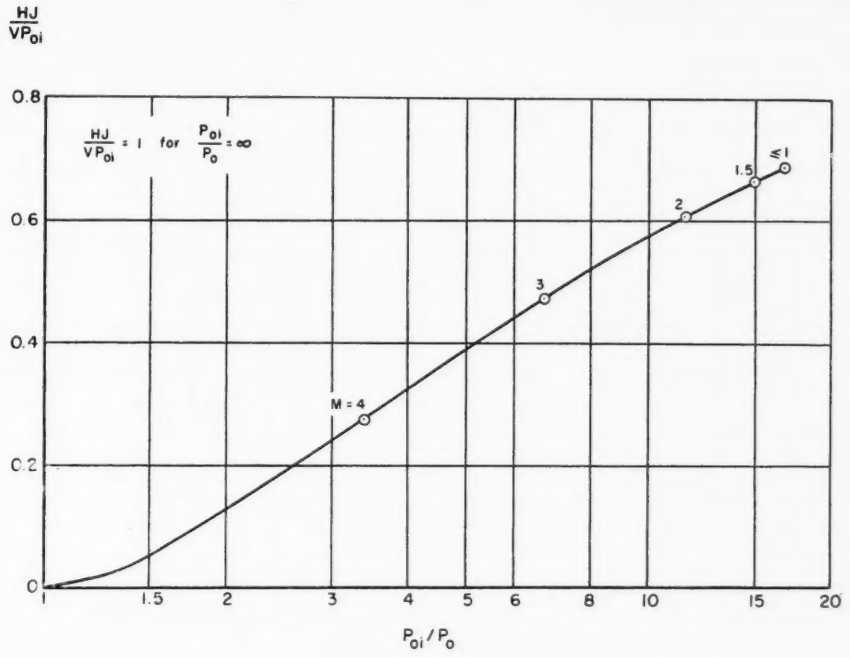

FIGURE 8. Heating requirements of a pressure storage drive.

of some difficulty, since the heat flow is unsteady and the air entry temperature varies with time. However, suitable methods of calculation were developed by Hausen[7], Pillow[8] and Judd[18].

Some notion of the required mass of the heat exchanger can be obtained by assuming that its average temperature drop is equal to, say, 1/3 of the maximum air temperature drop. On that basis, about 160 lb. of steel are required per square foot of tunnel working section area per second of running time.

The heat exchanger would have to be regenerated between, and possibly during, tunnel runs; for example, it could be brought to a uniform temperature by blowing hot air or by electrical heating with built-in elements. At the expense of some complication of the tunnel circuit, the waste heat from the compressor plant carried by high pressure air or coolant could be used to regenerate the heater, thus eliminating extra power load.

3.7. REDUCTION OF REYNOLDS NUMBER VARIATION WITH INCREASED STORAGE CAPACITY OR PRESSURE

Although a heater is indispensable for maintance of a constant Reynolds number in pressure-driven tunnels operated at constant stagnation pressure, a reduction in the Reynolds number variation can be obtained without a heater by merely increasing the storage capacity or pressure beyond the necessary minimum.

The following relation, derived from equations (11) and (13), holds for the storage volume or pressure and Reynolds number*, for a given duration of tunnel run, tunnel stagnation pressure and tunnel size:

$$\frac{V'}{V} = \frac{P_{01}'}{P_{01}} = \frac{1 - \left(\frac{P_0}{P_{01}}\right)^{0.714}}{1 - \left(\frac{R_1}{R_2}\right)^{1.93}} \quad . \quad . \quad (17)$$

For the already considered case of sonic speed, $P_{01} = 20$ atm. and $P_0 = 1{\cdot}2$ atm., the storage volume or pressure have to be increased by a factor of 5 to limit the Reynolds number increase to 10 per cent., or 3 times if a 20 per cent. variation in the Reynolds number were allowed. The corresponding stagnation temperature ratios are 1·076 and 1·15, giving temperature drops of about 20°C. and 38°C. respectively.

3.8. AIR DRYING

In order to eliminate adverse effects of condensation of water vapour on flow in the wind tunnel working section, the air must be dried to a low absolute humidity. The original German practice was to keep the water content in the vacuum-driven tunnels below 0·05 per cent. (dew point −22·5°C. at atmospheric pressure). This criterion was consistent with the quality of the velocity distribution originally obtainable with supersonic nozzles, and corresponded to a maximum condensation shock pressure rise of about 1·34 per cent[9]. In step with the improvement of flow velocity distribution in supersonic wind tunnels, the dryness requirements were raised and the present practice, followed in most American wind tunnels, is to dry the air to an absolute humidity of less than 0·01 per cent., corresponding, at atmospheric pressure, to a dew point of −40°C. Under these conditions condensation-free flow can be expected in vacuum-driven, atmospheric

*Assuming, for small changes of Reynolds number, a running time based on constant stagnation temperature.

tunnels (20°C. stagnation temperature) at Mach numbers up to 1·5, and the effects of condensation are negligible at higher speeds.

The required low air humidity is usually obtained in wind tunnel installations by passing the air through beds of desiccant, such as silica gel or activated bauxite (alumina). The drier system suitable for large, vacuum-driven intermittent wind tunnels is similar to that used in open-circuit, continuous installations, except that, due to relatively small total quantity of air passed through the tunnel, a smaller mass of desiccant needs to be used. The performance of a drier bed is known to depend on a number of factors, such as inlet absolute humidity and temperature, bed temperature and thickness and air velocity through the bed, but little information is available on quantitative effects of these variables and only general trends can be noted here. It is found that the adsorption capacity of desiccant decreases with increase in inlet absolute humidity and with decrease of bed thickness. Under similar conditions a higher useful bed concentration (*i.e.* maximum percentage of water by weight adsorbed by desiccant for a specified dryness of effluent air) is obtained with silica gel than with activated alumina: about 4 and 2 per cent. respectively for 12-in. thick beds, at inlet absolute humidities not exceeding 0·016 and at air velocities up to 100 ft./min. From the point of view of drying efficiency, alumina appears to be superior to silica gel and depresses the air dew point to about −46°C. compared with about −40°C. for silica gel. Also, for a given bed thickness, the pressure drop coefficient is appreciably smaller for 4-8 mesh alumina than for 3-8 mesh silica gel[10].

Although the actual choice of desiccant would depend largely on economic considerations, it appears that for large, vacuum-driven intermittent wind tunnel applications alumina has more favourable characteristics, in that it combines high drying efficiency and low pressure drop with a lower useful concentration suited to a relatively small air mass flow. Also, alumina is about 50 per cent. cheaper per pound than the silica gel.

The mass of desiccant required for a vacuum-driven intermittent wind tunnel can be related to the installed exhauster power. On the assumption of a 2 per cent. useful bed concentration and an atmospheric absolute humidity of 1·5 per cent., about 20,000 lb. of alumina are required per 1,000 h.p.hr. of tunnel operation or 27,000 lb. of tunnel air flow. At an air velocity of 100 ft./min. through the drier, a bed area of 400 ft.^{2} per square foot of tunnel working section area is required. If a 1-ft. thick alumina bed is used (pressure drop 3 in. water), about 9 minutes of tunnel running time can be obtained at tunnel sonic speed. Considering that a total running time of one minute per hour is reasonable for intermittent tunnel operation, the design figures given in this example, which must be regarded as an illustration only, appear well suited to an 8 hr./day tunnel running schedule.

The drier design discussed here is of the simplest type and does not contain any pre-drying equipment, such as air pre-cooling by means of water spray or coils, or equipment for cooling of desiccant beds.

The drier beds are usually reactivated by heating (with hot air) to some 180°C. and cooling to normal temperature; the regeneration system can be designed to complete the cycle of adsorption and reactivation in 24 hours. In small drier installations, cold flow reactivation between tunnel runs is sometimes used, but this results in a considerable complication of the drier system and would therefore not be favoured for large driers.

Particular attention, especially with driers for vacuum-driven tunnels, should be paid to air-tightness of the drier structure, so that moist outside air cannot by-pass the desiccant.

It is believed that if conservative design data, similar to those discussed here, are used, the design of a large drier does not present a difficult engineering problem, although the available experience is not extensive. As an example of a large drying plant one can mention the drier of the 8 × 6-ft.^{2} supersonic wind tunnel at the N.A.C.A. Lewis Flight Propulsion Laboratory at Cleveland, Ohio. This drier contains 2,200,000 lb. of alumina in eight 2-ft. deep beds and is reactivated by air heated directly by combustion of natural gas[11].

As an alternative to a large drier one might consider storage of dry air. In this case, the tunnel air, extracted from vacuum vessels, is exhausted by the compressor plant into storage tanks to which the wind tunnel intake is connected. The dry air storage tanks must be of the variable-volume, constant pressure type, the air being stored at all times at atmospheric pressure. With this arrangement only small static-type drier installation is needed, to take care of air leakage in the tunnel circuit. The required dry air storage volume is large and amounts, at sonic speed, to 650 ft.^{3} per square foot of tunnel working section area per second of running time. This gives, for a 6-ft. square tunnel running for 20 sec., a volume of 470,000 ft.^{3}

The amount of water to be removed by the drier is much smaller in the case of pressure storage drive, since most of the moisture is eliminated during compression. At 20 atm. and 20°C., saturated air contains 0·07 per cent. of water, so that only a relatively small drier, of the static type, is required. On the assumption of a 4 per cent. (for silica gel) useful bed concentration, about 200 lb. of desiccant would be required per 1,000 h.p.hr. of tunnel operation.

3.9. WIND TUNNEL DUCT

So far we have examined the design and performance of various components of intermittent wind tunnel installations with the exception of the wind tunnel proper. This apparent omission is not unintentional: the wind tunnel duct, which usually consists of entry contraction, nozzle, working section and diffuser, is essentially similar in continuous and intermittent wind tunnels and therefore need not be considered in any detail here, in a work particularly concerned with discontinuous tunnels. We will restrict ourselves to note that, unlike a continuous tunnel, an intermittent one must be equipped with an adjustable diffuser. Data concerning suitable diffuser geometry will be found in Ref. 5; since simple geometrical shapes are adequate, the mechanical design

of a variable diffuser and its drive does not present difficulties (*see also* Section 4.1). Otherwise an intermittent tunnel duct is much simpler than its continuous counterpart: cascaded corners and cooler sections are eliminated, as well as any complications of the circuit usually required to cover an appreciable speed range with a continuous drive. On the other hand, in view of extremely large Mach number range available with intermittent drive, it might be desirable to include in the tunnel duct a wide-range, variable Mach number nozzle together with a transonic working section. Alternatively, these two components might be interchangeable or a separate tunnel duct for high Mach number range might be preferred. This is a practical solution, since, unlike the case of continuous drive, another tunnel duct is easily connected to the elements of intermittent drive.

4. Operation of Intermittent Wind Tunnels and Model Testing

Having examined the design and performance of intermittent wind tunnel installations, we will now turn our attention to the *operation* of intermittent wind tunnels; the techniques differ in many cases from the conventional ones developed for continuous tunnel testing.

4.1. MACH NUMBER CONTROL

Supersonic speeds are in general obtained in wind tunnels by means of appropriately shaped convergent-divergent nozzles, Mach number being constant so long as the nozzle shape remains unchanged. Since at sub- and transonic velocities the Mach number is not determined by the shape of the tunnel duct upstream of the working section, in continuous tunnels it is controlled in this speed range by regulation of the compressor speed. The steadiness of Mach number then depends on the quality of the drive speed control system. Due to large installed power and the required high performance, the latter increases considerably the complexity and cost of the drive.

These difficulties are completely eliminated with the intermittent drive, the working section Mach number being controlled over the whole speed range by purely geometrical means. At subsonic speeds the working section Mach number is maintained at a steady value by choking the tunnel flow downstream of the working section, by means of an adjustable diffuser. Thus at subsonic speeds the diffuser throat performs the function of a nozzle throat at supersonic velocities.

The setting of the diffuser throat is not a unique function of the working section Mach number, but depends on upstream losses, produced by the model and its supports. With models driven over an incidence range during each tunnel run, the losses and therefore Mach number would vary and this could be particularly serious at Mach numbers close to one, in the range in which Mach number is particularly sensitive to area changes.

A quantitative estimate of the Mach number changes (with a fixed diffuser throat), due to variation of the model drag, can easily be made if it is assumed that the entropy increase of tunnel flow corresponds to dissipation of drag energy at constant pressure. The entropy increase per pound of air is thus given by:

$$\Delta s = \frac{v_\infty D}{JWT_\infty} \quad . \quad . \quad . \quad (18)$$

and the effective stagnation pressure $\overline{P}_0$ is equal to

$$\overline{P}_0 = P_0 e^{-\frac{J}{R}\Delta s} = P_0 e^{-\frac{1}{2}\gamma M^2 C_D \frac{S}{A}} \quad . \quad (19)$$

where R is here the gas constant.

Since flow velocity in the diffuser throat is sonic and therefore dependent only on the tunnel stagnation temperature, a relative decrease in the stagnation pressure is equivalent to an equal relative decrease in the diffuser throat area. Thus the effective expansion ratio is equal to

$$\frac{A}{\overline{A}_d^*} = \frac{A}{A_d^*}\frac{P_0}{\overline{P}_0} \quad . \quad . \quad . \quad (20)$$

where A/A_d^* is the actual working section/diffuser throat area ratio. From the actual and effective area ratios and equation (2) the change in the free stream Mach number is obtained.

Calculations were made for a typical delta wing aircraft model and it was found that over an incidence range from 0° to 20° the working section Mach number would change, with a fixed diffuser throat, from 0·8 to 0·773 and from 0·9 to 0·84.

Since it is convenient to maintain a constant Mach number while the model attitude is changed, the above considerations indicate that for sub- and transonic operation intermittent wind tunnels should be equipped with an automatically controlled diffuser throat. The procurement of a suitable servo-mechanism, sensitive to the working section static pressure and driving one wall of a two-dimensional diffuser, should not prove too difficult or expensive.

The experience obtained with the N.A.E. 30-inch high-speed tunnel shows that the above refinement, at least for relatively small tunnels and non-driven models, can be dispensed with and that with some practice a tunnel operator can maintain the Mach number constant to within 0·01, by manual adjustment of diffuser throat gap with each change in the model incidence.

Before leaving the subject of Mach number control, it is pertinent to note that the variable throat system used in intermittent tunnels offers one additional advantage over conventional type of subsonic speed control, in that it prevents disturbances, originating downstream of the working section (*e.g.*, in the diffuser) from reaching the model. Several workers[12, 13] have shown that this effect may be appreciable at transonic speeds and that it is eliminated by a sonic diffuser choke.

4.2. TUNNEL STARTING AND STOPPING

The starting and stopping of flow in supersonic wind tunnels introduces several problems, which can be grouped under headings of (*i*) time to start and stop, (*ii*) starting and operating pressure ratios, (*iii*) model loads, (*iv*) loads on tunnel structure.

Usually a relatively long time is required for starting and stopping of continuous wind tunnels. This is due to limitations of the starting torque, the attendant necessity of reducing pressure in the tunnel circuit at starting and to large inertia of compressor and motor rotors which require electrical braking on stopping. Since tunnel stoppages are necessary for making even small model changes and adjustments, the above delays reduce the output of continuous wind tunnels.

Intermittent wind tunnels are of course free from the above deficiencies, being started and stopped instantaneously by quick-acting valves and usually without help of auxiliaries such as compressors, exhausters, brakes, and so on. Moreover, in intermittent tunnels minor model adjustments can be made between tunnel runs, with no adverse effect on the rate of testing.

As regards starting and operating pressure ratios, it is evident from Table I and Fig. 4 that at Mach numbers larger than 3 appreciably higher starting pressure ratios are required. This introduces no difficulty with vacuum storage tunnel drive, since the available pressure ratio is very large at the start of a tunnel run and only gradually decreases to the minimum operating value at the completion of the run. Thus the vacuum storage drive is even better matched to the supersonic tunnel requirements than the pressure storage drive, which operates, like a continuous wind tunnel, at essentially constant tunnel pressure ratio. Provided that a suitably high storage pressure (say 20 atm.) is used, the required starting pressure ratio can be made momentarily available at the start of a run.

The question of starting and stopping model loads is of interest in intermittent wind tunnels, particularly of the pressure storage type, which operate at high densities. With continuous tunnels the starting model load problems are somewhat different, in that the stagnation pressure can be arbitrarily decreased during starting and stopping and the establishment of supersonic flow takes a relatively long time. The slow starting and stopping of continuous wind tunnels is apt to lead to flutter failure of models if special precautions are not taken and is considered a disadvantage compared with instantaneous operation of intermittent tunnels.

No starting difficulties are anticipated with vacuum-operated intermittent wind tunnels, in which models are being successfully tested at both sub- and supersonic speeds at fixed incidence. If necessary, an appreciable reduction of model loads can be obtained by throttling the intake and starting and stopping the tunnel at lower than atmospheric stagnation pressure[16].

Compared with a vacuum-driven tunnel, dynamic pressures and model loads obtained in a pressure-driven one are much higher, the ratio being given directly at any Mach number by the stagnation pressure expressed in atmospheres, Fig. 4, Tables I and III. The corresponding dynamic pressures are shown in Fig. 9. At $M = 4{\cdot}5$, the starting model loads are 15 times as high as with the vacuum storage drive and the dynamic pressure amounts to $\frac{3}{4}$ atm., Fig. 9, curve *s*. In the process of starting and stopping of high Mach number flows, usually an asymmetric jet, detached from the curved nozzle walls, is formed and causes large transient angles of attack and model loads. The combination of high stagnation pressures with asymmetrical transient flow configuration may cause excessive loads and vibrations of models in pressure storage driven tunnels and may therefore require consideration of special starting techniques. The transient angles of attack may be reduced by mounting the model with its lifting surface in the plane of two-dimensional nozzle flow. Quickly operated, auxiliary model supports might be devised for use during starting and stopping only. Finally, a diffuser ejector or an auxiliary vacuum vessel might be used to reduce the starting pressure to the operating value.

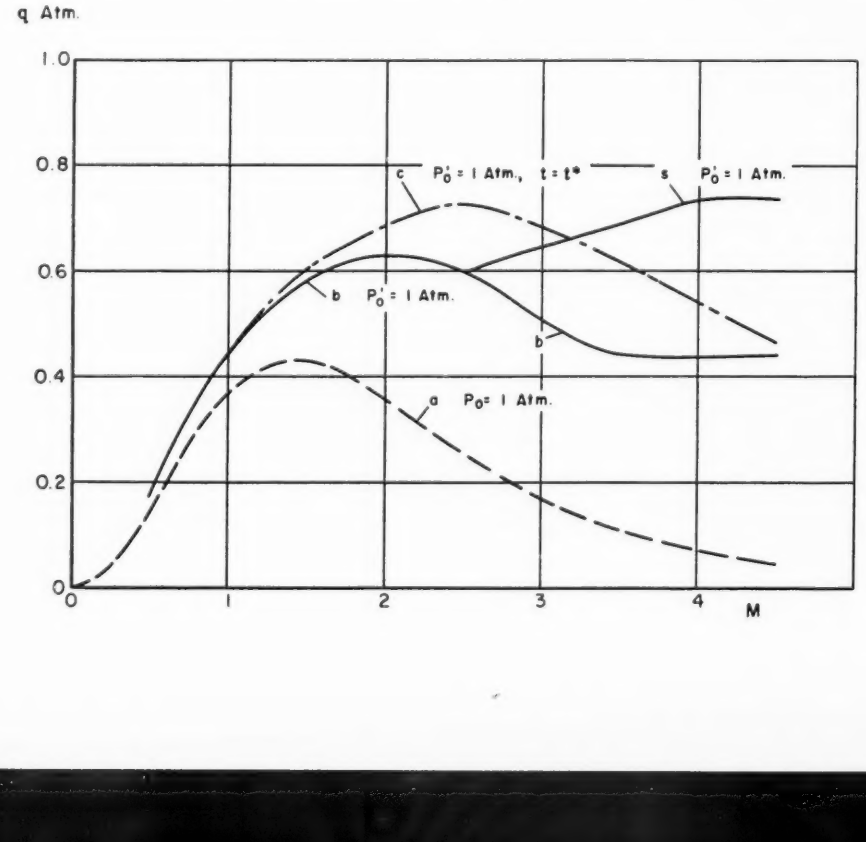

FIGURE 9. Dynamic pressure in intermittent wind tunnels.

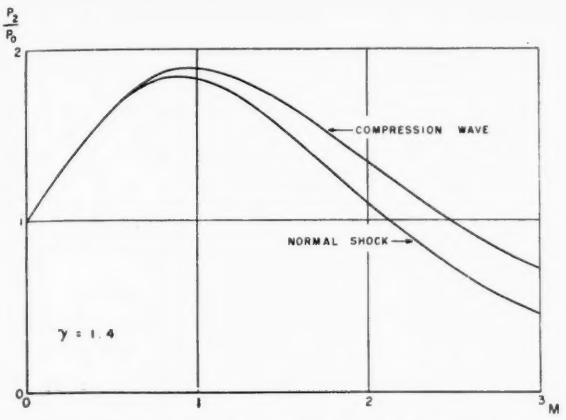

FIGURE 10. Theoretical pressures due to quick closing of tunnel valve (vacuum storage drive).

The last of the problems to be here considered is that of the starting and stopping loads on the tunnel structure. Pressures higher than stagnation will not develop in pressure storage driven tunnels and on starting of the vacuum-driven ones. However, as shown below, pressures appreciably larger than stagnation may be reached on stopping of the vacuum-driven tunnels.

The maximum amplitude of the compression wave caused by valve closing in a vacuum-driven tunnel is readily calculated from one-dimensional unsteady motion and normal shock theory[6]. The highest pressure would be attained with a rate of valve movement such as to cause the formation of a simple, isentropic compression wave. The maximum pressure P_2 produced by such a wave is given by

$$\frac{P_2}{P_0} = \left(1 + \frac{\gamma-1}{2}M\right)^{\frac{2\gamma}{\gamma-1}}\left(1 + \frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma}{\gamma-1}} \quad . \quad (21)$$

where M is the Mach number at the valve and P_0 is the tunnel stagnation pressure.

If the valve were assumed to close instantaneously, a normal shock would be propagated upstream and a pressure

$$\frac{P_2}{P_0} = \left[\frac{2\gamma}{\gamma+1}\left\{\frac{\gamma+1}{4}M + \left[\left(\frac{\gamma+1}{4}M\right)^2 + 1\right]^{\frac{1}{2}}\right\}^2 - \frac{\gamma-1}{\gamma+1}\right]\left(1 + \frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma}{\gamma-1}} \quad . \quad . \quad (22)$$

would be attained.

The above functions are plotted in Fig. 10 and it is seen that pressure of almost twice the tunnel stagnation pressure may theoretically develop at transonic speeds. This prediction was qualitatively confirmed by tests made with the N.A.E. 30-in. intermittent wind tunnel, in which appreciable super-atmospheric pressures were observed on valve closing before the motion of the valve was slowed down as already described.

4.3. TESTS IN INTERMITTENT WIND TUNNELS AND INSTRUMENTATION

With modern instrumentation techniques, measurements can be made and recorded within a small fraction of a second and therefore the short running time of intermittent wind tunnels does not restrict their usefulness, except in cases in which physical phenomena require a relatively long time to reach a stable condition. For instance, heat transfer* or combustion tests can be better conducted in continuous wind tunnels. However, there appears to be no objection in obtaining force and, if the pressure line lag is small, pressure data from models driven during a tunnel run over an incidence range. Rotation of the model will not affect its aerodynamic characteristics provided linear velocities due to rotation are small compared with the free stream velocity†. It is found that even for relatively large models, of a size suitable for a 6-ft. square wind tunnel, the ratio

$$\frac{\omega l}{2v_\infty} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

is of the order of 10^{-4} at sonic speed for $\omega = 1$ deg./sec., and therefore the effect of model rotation can be presumed to be negligible for practical angular velocities. The same is found if changes in the boundary layer flow due to model rotation are considered. It can be shown[6] that the significant time is in this case of the order of the time taken by the model to travel a distance equal to its own length, and therefore quite small (10^{-2} to 10^{-3} sec.)

A balance system suitable for use with driven models could consist, for example, of a strain gauge internal model balance attached to an externally driven incidence gear. Depending on required output and acceptable cost, the recording system could range from completely automatic, high speed computors and printers to automatic film or chart recorders from which balance outputs have to be read off after each tunnel run. A relatively simple instrumentation system, of the latter type, is at present under development in the N.A.E. High Speed Aerodynamics Laboratory. Balance outputs are directly recorded on a paper chart by high-speed, self-balancing, Leeds and Northrup Speedomax potentiometers. The chart is driven at 1 in./sec. and is 10 in. wide, this width corresponding to a minimum range of 1 mV. Controls are provided for variation of range (1 mV. to 20 mV.), zero suppression, gain and damping. The balancing time is about one second for a full range variation of input signal but small amplitude oscillations can be recorded for frequencies up to about 20 c.p.s. The time response of the recorders can be judged from Figs. 11 and 12. Fig. 11 shows a typical record obtained with fixed model incidence from a strain gauge balance. Depending on the amplitude, a steady reading is reached in one second or less. The ability of the potentiometer to follow a fluctuating input signal is

*It is interesting to note that probably the first heat transfer tests at supersonic velocities were made during the war, in Germany, in intermittent wind tunnels.

†This problem was considered by Glauert[14].

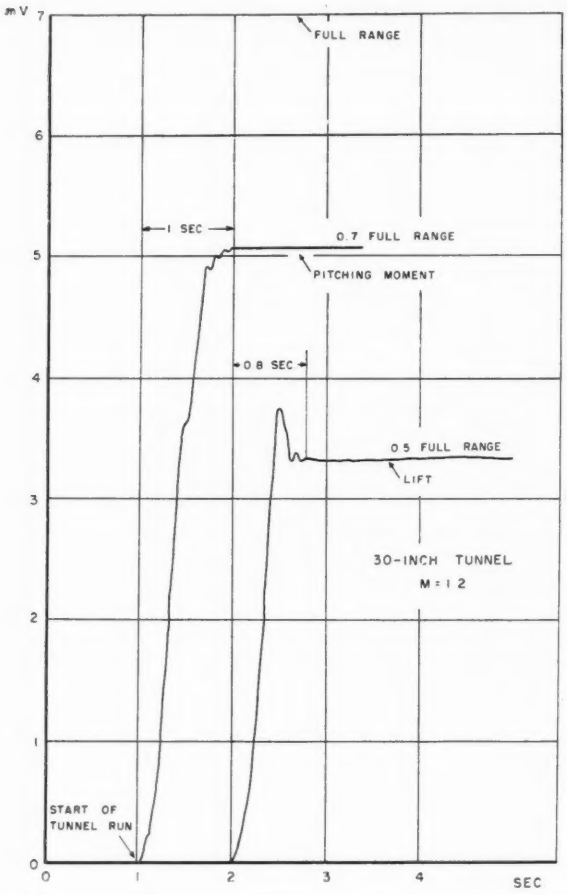

FIGURE 11. Response of Speedomax recorder to strain gauge balance output.

illustrated by the trace of Fig. 12. In practice, this is often useful for determination of onset of buffeting or detection of low frequency flow instabilities.

In order to check the suitability of the above instrumentation for driven model tests, an existing 10-in. tunnel, external strain gauge balance was fitted with an electrical drive, the assembly being shown in Fig. 13(*a*). The balance, with the model attached, is actuated by means of a cam which can be designed to provide continuous or step-like variation of incidence at any desired rate.

In Fig. 13(*b*) a three-component half-model balance and its cam-drive are shown mounted on the 30-inch wind tunnel. Typical results obtained with a continuously driven model are shown in Fig. 14. In order to correlate the continuous trace with the nominal model incidence, the chart is marked at one degree intervals by a solenoid pen driven from the actuating cam shaft by means of a microswitch-discharged, condenser circuit. Thus the accuracy of the continuous record can be checked by superposition of readings obtained at the same incidences with the model stationary. The agreement between the two records, as shown in Fig. 14, is

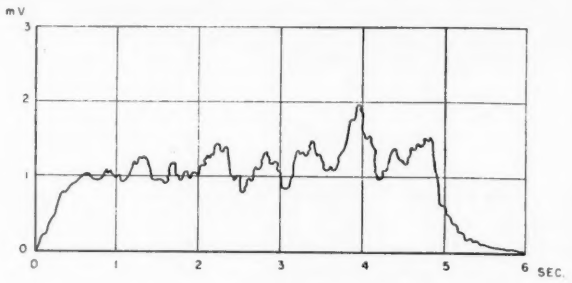

FIGURE 12. Trace of fluctuating pressure obtained with Speedomax recorder and Statham transducer.

satisfactory*, the full range of readings being covered in less than 10 seconds.

With the continuous model drive, the aerodynamic derivatives with respect to incidence are given directly by slopes of the records. However, in general the records would be subject to correction due to interaction of components and model deflection under load†, as indicated in Fig. 14.

With the step-like variation of incidence the slopes are not directly obtainable but errors due to instrument lag and the necessity of incidence indication on the recorder chart are eliminated. Typical traces obtained with the step system are shown in Fig. 15, for steps of same frequency but of two different amplitudes. The minimum time required to obtain a steady reading depends on the amplitude of the step. The response of the recorders to a step function is shown on the right of Fig. 15. It is estimated that about one-half second is required to obtain steady reading with steps of 5 per cent. maximum reading amplitude, and about $\frac{3}{4}$ second for steps of double this amplitude. Thus complete range of model incidence, of say 20 one-degree intervals, could be covered in about 10 seconds. It seems therefore that, from the point of view of minimum duration of tunnel runs, the continuous and step systems are equivalent.

Next to the force measurements, most common tunnel tests are pressure plots of models. In continuous wind tunnels pressures are usually measured with banks of multi-tube manometers. This method can also be used in intermittent tunnels, provided tunnel runs of about 15 sec. or more are possible. The model must then remain in a fixed attitude, and, if read visually, the manometer levels are frozen before the end of the run by means of a cut-off valve.

The time required to obtain pressure readings can be appreciably reduced if electrical pressure transducers are used in place of tube manometers. Using the above-mentioned Speedomax potentiometers in conjunction with Statham strain gauge pressure transducers, static

*In some of the other tests made at different rates of incidence variation, the continuous trace was found to lag slightly, to the extent of less than one per cent. of maximum reading.

†In general, with driven models, the balance measurements are also subject to static tare corrections; these are eliminated if the model rotates in the horizontal plane.

pressure readings are obtained in 1 to 3 seconds, depending on the size of pressure hole and length of the connecting tube. Typical pressure records are shown in Fig. 16. Since it is most convenient from the point of view of model construction to use half-models for pressure plotting tests, tube connections can be made short even for large models. Alternatively, if only a small number of pressure taps is required, transducers imbedded in the model surface may be used.

The accuracy of unbonded strain gauge type pressure transducers used in conjunction with Speedomax recorders was found completely satisfactory, the probable overall error in the calibration factor of $\pm 0{\cdot}3$ per cent. being obtained.

It should be noted here that, in general, strain gauge instrumentation is particularly well suited to intermittent wind tunnels: with the short running times no appreciable temperature changes can take place and no trouble is experienced with the zero drift of strain gauge bridges.

In addition to the standard force and pressure tests already discussed, there is no reason why other types of tests, such as flutter or oscillating model tests, should not be carried out in intermittent wind tunnels.

In fact flutter tests may be particularly conveniently carried out in pressure storage driven intermittent tunnels, for two reasons: the onset of flutter can be determined by changing tunnel stagnation pressure and the tunnel quickly shut down to prevent model destruction. Should the model disintegrate, there is little danger of any serious damage to a non-return intermittent type tunnel.

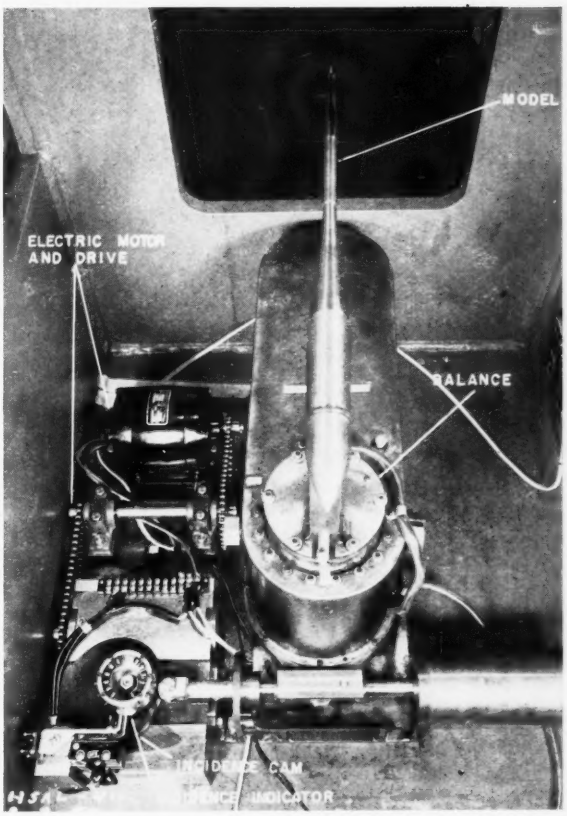

FIGURE 13(*a*). Electrically-driven balance.

4.4. MODEL REYNOLDS NUMBER

Usually two factors, namely the tunnel working section size and the flow stagnation pressure, determine the model Reynolds number at any given Mach number. In practice, these two factors are not always completely equivalent, as in the case of routine testing of aircraft and missile models. It is considered that for such tests a certain minimum model and therefore tunnel size should be specified; otherwise the manufacture of complete models, with which often loads on control surfaces need to be measured, becomes unduly difficult and expensive. Available experience indicates that on this basis the tunnel working section should not be smaller than about 4-ft. square.

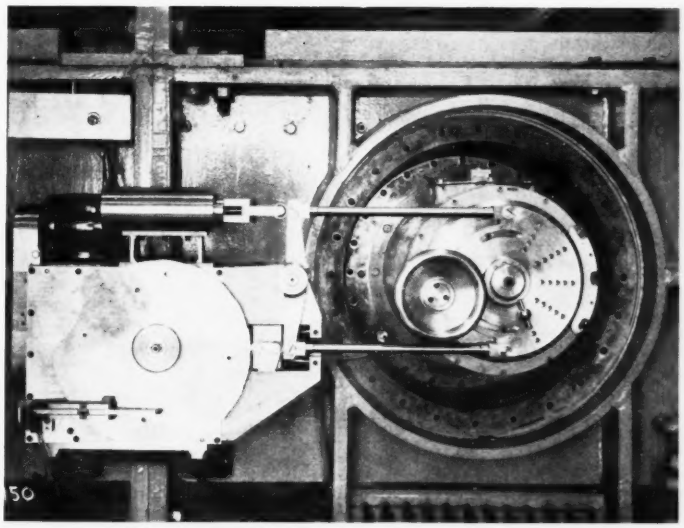

FIGURE 13(*b*). Three-component half model balance (*right*) with cam-drive (*left*) attached.

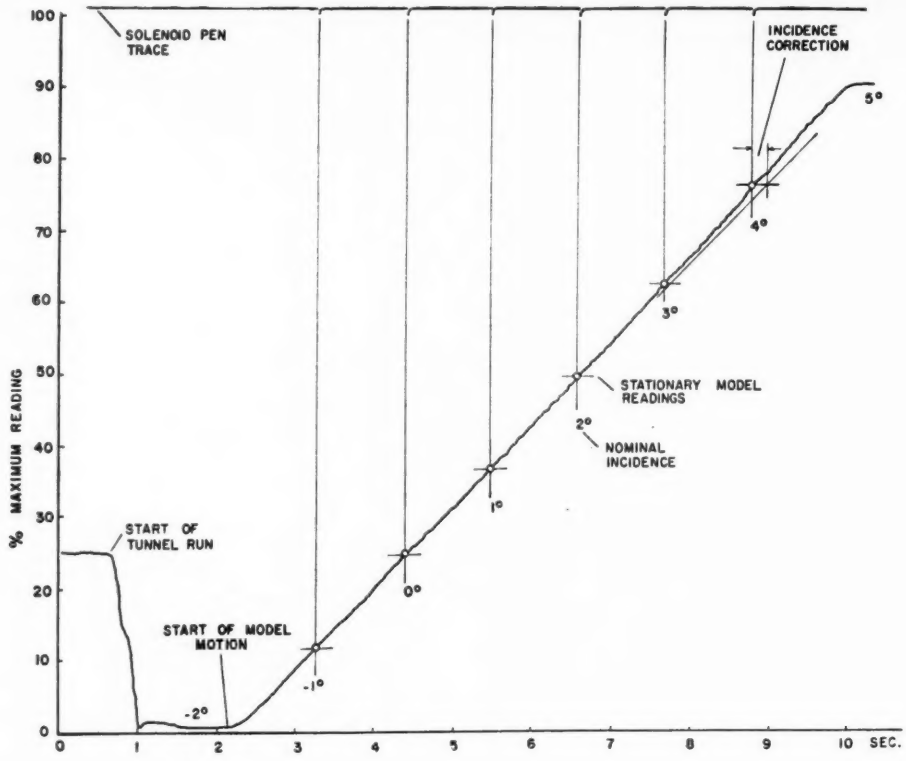

FIGURE 14. Pitching moment measurements obtained with stationary and continuously driven model (10 inch wind tunnel, $M = 1{\cdot}6$).

From the point of view of aerodynamic characteristics, there appears to be no well-defined "minimum useful" model Reynolds number, model tests being invariably carried out in whatever facility is available at the time, and results being seldom discarded on account of too low a Reynolds number. From survey of test data it seems that large variations in aerodynamic characteristics occur at model Reynolds numbers (based on mean aerodynamic chord) smaller than about 2 million, and that model Reynolds numbers of 5 million are desirable.

In accordance with the above criteria of minimum tunnel size and model Reynolds number, the Reynolds numbers obtainable in a 6-ft. square vacuum-driven tunnel and a 4-ft. square pressure storage type tunnel were computed for "typical" models of a supersonic fighter and a high speed subsonic transport aircraft.

Leading characteristics of the two models are outlined in Table VI. In the case of the high aspect ratio transport model, the span is assumed to be the limiting dimension and is taken as 2/3 of the (square) tunnel side. This corresponds to a 0·6 per cent. blockage, a figure conservative even for tests in a closed working section at high subsonic Mach numbers. The fighter model is taken as having a 1 per cent. blockage at subsonic speeds and, at supersonic speeds, to be free from wave interference at $M > 1{\cdot}2$, this requirement corresponding to a blockage of 0·5 per cent.

In addition, a missile model is considered in the higher supersonic speed range. Its length is such as to ensure freedom from wave interference at $M > 1{\cdot}6$ and a ratio m.a.c./length = 0·2 is assumed.

The Reynolds numbers computed for the above models are plotted in Fig. 17 in terms of Mach number. For the 4-ft. wind tunnel, stagnation pressures as given for constant running time by curve *c*, Fig. 4 (with atmospheric exhaust pressure) were used in computation of the Reynolds number. In all cases Reynolds number exceeds two million at $M > 0{\cdot}5$ and, for the fighter model, five million over the speed range up to twice the speed of sound. In the supersonic range the model Reynolds number increases with increasing Mach number in the pressure storage driven tunnel. This is due to increase in the stagnation pressure, as illustrated by curve *c*, Figure 4. The variation of Reynolds number based on 1-ft. length for the two types of tunnel drive is shown in Fig. 18 and corresponds with the trends exhibited by the variation of model Reynolds number (Fig. 17).

TABLE VI

CHARACTERISTICS OF TYPICAL AIRCRAFT MODELS

	High speed transport model	*Supersonic fighter model*
Wing L.E. sweep	32 deg.	58 deg.
Aspect ratio	6·5	2·35
Taper ratio	0·333	0·185
Span/Length	0·93	0·66
Frontal area/(Span)^2	0·014	0·025
(m.a.c. Wing)/Span	0·165	0·49

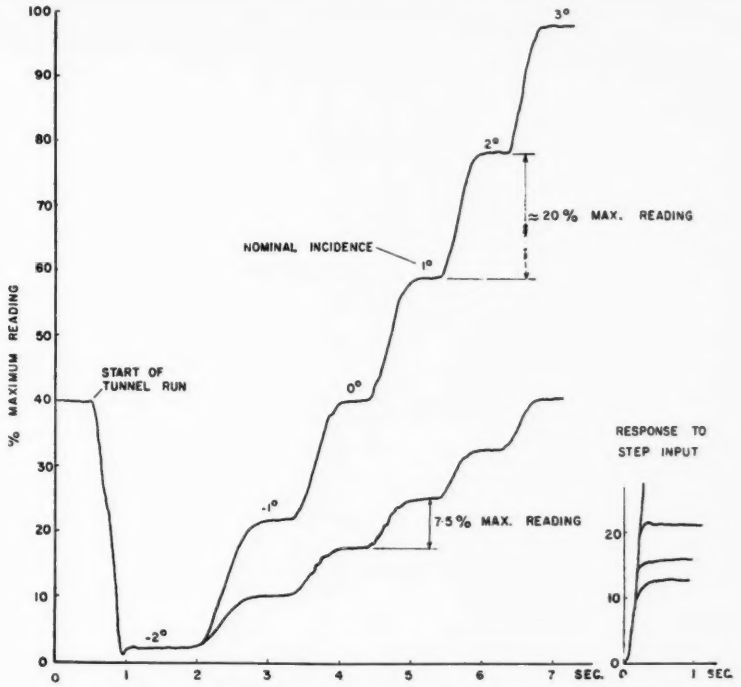

FIGURE 15. Pitching moment measurements obtained with step-driven model (10 inch wind tunnel, $M = 1{\cdot}6$).

With both types of drive Reynolds numbers much higher than those shown in Fig. 17 can be obtained at higher supersonic speeds, since appreciably larger models can then be used. Compared with an interference free model at $M = 1{\cdot}4$, the model size can be doubled at $M = 2{\cdot}25$ and tripled at $M = 3{\cdot}2$.

It should be realised that, with the pressure storage driven tunnels, very large model Reynolds numbers can be obtained with short running times. However, as discussed in Section 4.2, the model loads might be then excessive due to large stagnation pressures and half-model technique might have to be used.

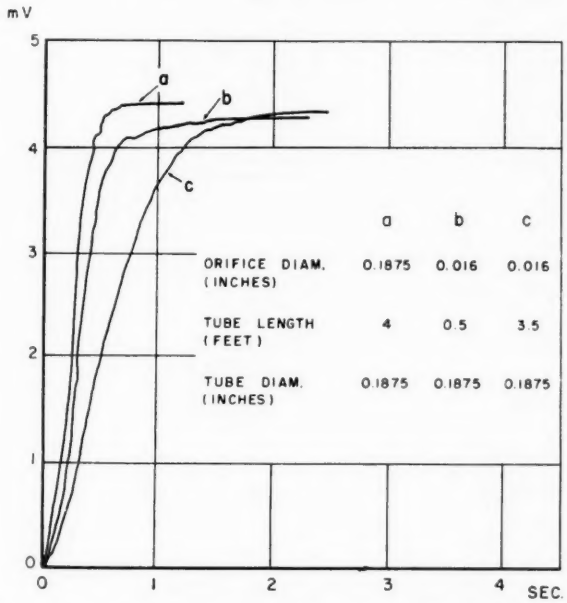

FIGURE 16. Typical pressure measurements obtained with Statham strain gauge transducers and Speedomax recorders.

5. Examples of Intermittent Tunnel Installations

Having examined the more important aspects of design, performance and operation of intermittent wind tunnels, we will now consider, in order to get some idea

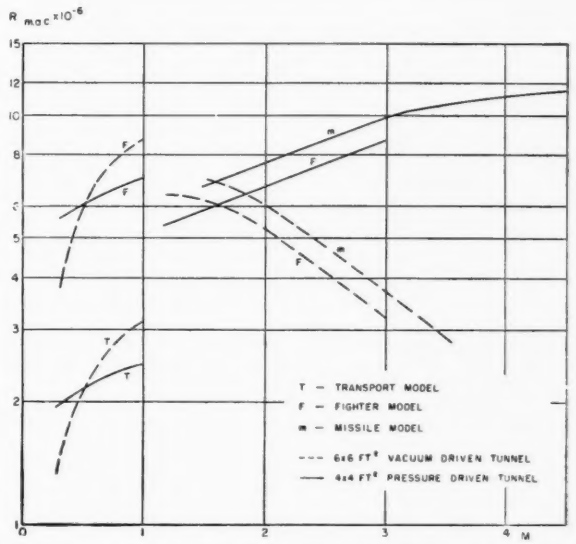

FIGURE 17. Model Reynolds number based on m.a.c. (tunnel stagnation temperature 15°C.).

of the magnitudes involved, two concrete examples of intermittent installations: a 6-ft. square vacuum-driven tunnel and a 4-ft. square pressure driven tunnel. These sizes have been chosen as approximately the minimum ones which will give a satisfactory model size and Reynolds number, as already discussed. As regards the duration and frequency of tunnel runs, three 20-second runs per hour have been specified. This is perhaps a rather conservative duration of tunnel run, but all data excepting the storage volume, which has to be reduced in proportion, is equally applicable to shorter but more frequent runs (*e.g.* six 10-sec. runs per hour). In the case of the 4-ft. square pressure storage tunnel a constant Reynolds number was specified and heater capacity was estimated accordingly. The data relating to the two tunnel installations follows:

	6×6 ft.^{2} Tunnel *Vacuum Storage Drive*	4×4 ft.^{2} Tunnel *Pressure Storage Drive*
Stagnation pressure	1 atm.	>1 atm., variable with M.
Storage pressure	vacuum (100 mm. Hg abs.)	20 atm.
Exhauster or compressor power	5,700 h.p.	5,800 h.p.
Power dissipated in cooling	2,000 h.p.	5,800 h.p.
Storage volume	765,000 ft.^{3}	14,400 ft.^{3}
Storage vessels	3 × 79 ft. diam. spheres, 1·4 in. wall thickness or one, spherical segment vessel.	30 ft. diam. sphere.
Quick-acting valve	9·6 ft. diam. or $3 \times 5{\cdot}5$ ft. diam.	5·7 ft. diam. or 2×4 ft. diam.
Drier (for 8 hr. tunnel operation)		
Desiccant	900,000 lb. alumina (1·5 per cent. air abs. hum.).	9,400 lb. silica gel.
Desiccant bed area	18,000 ft.^{2}, 1 ft. bed thickness.	——
Reactivation (8 hr. heating, 8 hr. cooling cycle) equipment:		
Heater capacity	7,500 kw.	65 kw.
Cooler capacity	2,200 p.h.	20 h.p.
Heater capacity (tunnel air)	——	900,000 C.H.U./hr. or 650 h.p.
Heater weight	——	23 tons.

Although these figures are approximate only, they are believed to be sufficiently reliable to enable us to compare the two installations.

With regard to design complexity, the pressure storage drive requires an automatic stagnation pressure control but a very much smaller drier than the vacuum-driven tunnel. Also, depending on the specified constancy of Reynolds number, the pressure storage installation must include an air heater or be designed for larger than the above given storage pressure or volume (*see* Section 3.7).

These complications appear to be more than compensated for by the general compactness of the pressure-driven installation compared to the vacuum one. This

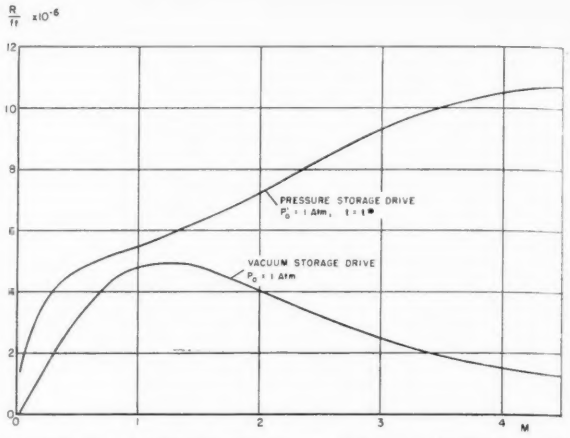

FIGURE 18. Reynolds number per foot in intermittent wind tunnels (stagnation temperature 15°C.).

is particularly evident in such items as storage volume and drier installation. Furthermore, it should be remembered that, by merely providing for a higher storage pressure, or using a small running time, a pressure storage type installation can give practically any desired model Reynolds number, much in excess of the minimum values here considered. On the other hand, since with the vacuum storage drive the Reynolds number is only dependent on the tunnel size, it is in practice restricted to much smaller values.

Thus on the whole, the pressure storage drive appears both aerodynamically and economically superior to the vacuum type of drive.

6. Installation Utilising Air Storage at High Pressure

In the discussion of pressure driven intermittent wind tunnels a relatively low storage pressure, of 20 atm., was assumed. The merits of this somewhat arbitrarily chosen value will be here briefly examined by comparing tunnel drives employing high pressure storage, of 2,000 lb./in.^{2} abs. (136 atm.) and 4,000 lb./in.^{2} abs. (272 atm.) with the example already considered. The data for the high pressure installations is based on the current American experience[17].

The essential features of the low and high pressure storage installations are indicated in the table below. In all cases the tunnel size and stagnation pressure (hence also model Reynolds number), duration and frequency of runs were kept constant.

According to Table VII, the high pressure drives do not appear more advantageous than the low pressure ones. While with the high pressure drives the weight of the storage vessels is not appreciably changed, the compressor power and cooling and heating* loads are considerably increased. Furthermore, the handling of

*The heating load as estimated for the high pressure cases is probably somewhat excessive since, although it includes the Joule-Thomson effect, equation (15), it neglects the heat capacity of the storage vessels.

TABLE VII

COMPARISON OF LOW AND HIGH PRESSURE STORAGE TUNNEL DRIVES

4×4 ft.^{2} tunnel, three 20 sec. runs per hour

Stagnation pressure	$\geqslant 1{\cdot}2$ atm. as given in Table I with $P_0' = 1$ atm. (*i.e.* atmospheric exhaust)		
Storage pressure			
lb./in.^{2} abs.	300	2,000	4,000
atm.	20	136	272
Storage volume (ft.^{3})	14,400	1,850	925
Weight of storage vessel (lb.)	270,000	250,000	250,000
Compressor power (= cooling load) (h.p.)	5,800	7,200	8,000
Heater load (h.p.)	650	1,000	1,250

high pressures requires in many instances specialised design and the use of non-standard components of equipment.

7. Relative Merits of Continuous and Intermittent Wind Tunnel Installations

Certain design and performance features of intermittent and continuous wind tunnels were already compared in the foregoing discussion. The main issues arising from such comparison will be summarised here and their effects on complete installations considered.

First of all it was shown that, unlike the case of drives of continuous tunnels, the characteristics of intermittent drives are well matched to the tunnel pressure ratio-mass flow requirements. Secondly, in intermittent installations the wind tunnel duct proper can be regarded as separated from all other components, the design of the two parts of the installation being mutually unaffected by their respective requirements. It is mainly for these two reasons that, in intermittent installations, high performance, superior to that obtainable in a single continuous tunnel, is combined with design simplicity—a situation which can never be realised in continuous wind tunnels. In fact, except for the tunnel duct proper and such unorthodox (but essentially simple to construct) items as large driers or heaters, only standard, commercially available machinery and steel work are

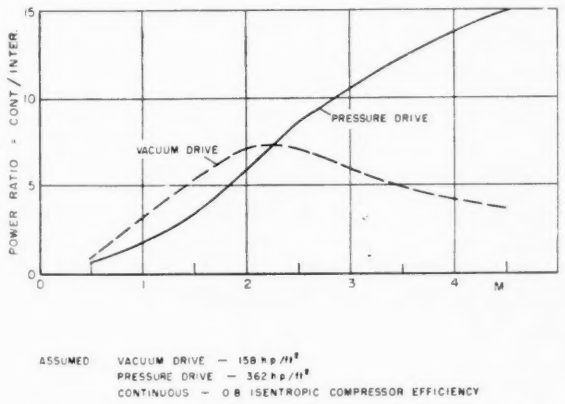

FIGURE 19. Ratio of power required for continuous and intermittent wind tunnels (at equal Reynolds numbers).

required in intermittent tunnel installations. This, together with the application of the principle of energy storage, results in overall economy when compared to equivalent (in Mach and Reynolds numbers) continuous installations. The saving in drive power alone is illustrated in Fig. 19, where powers required by a continuous tunnel driven with a compressor of 80 per cent. isentropic efficiency are compared with the ones needed to obtain 60 sec. of running time per hour with intermittent tunnels at equal Reynolds numbers. At Mach numbers exceeding 1·5, continuous drive power is from 5 to 15 times larger than that of the intermittent drive.

Discontinuous testing with relatively short running times is the price which one has to pay for the above advantages. With respect to force and pressure measurements, this is not as serious a penalty as it might first appear. Provided suitable instrumentation, which can be built up from commercially available equipment, is used and a range of model attitudes is covered during each tunnel run, the output of test data from an intermittent tunnel is comparable to the output of conventional continuous tunnels. Certain types of tests, such as heat transfer measurements, are certainly better conducted with continuous flow.

Subject to the above limitations, operation and model testing are in many respects carried out more conveniently with intermittent than continuous tunnels. Model and working section accessibility are improved with instantaneous tunnel starting and stopping, long running up, shut down and pumping periods being eliminated. Adverse thermo-electrical effects on instrumentation are largely avoided. Moreover, Mach number control is achieved independently of the drive, which operates at constant speed. Specialised techniques, involving, for instance, working section boundary layer control or partial removal of tunnel flow, are easliy introduced in an intermittent installation by use of small auxiliary vacuum capacity.

Finally, the potential development possibilities of intermittent and continuous tunnel installations need be considered. During the last decade it was found desirable to increase the Reynolds and Mach number range of many large wind tunnels and it seems likely that the same trend will continue, particularly with respect to the Mach number. Whereas the Reynolds number can be relatively easily increased in continuous tunnels by augmentation of the drive power, this is not true with respect to the Mach number, which would require an increase in the pressure ratio and therefore a redesign of the compressor. The situation is reversed in the case of an intermittent installation, which is essentially committed to a constant Reynolds number, but has a very wide Mach number range, somewhat dependent, at the upper limit, on the running time. However, with the pressure storage drive there is no difficulty in obtaining as high a Reynolds number as is desired. Furthermore, the utilisation of an intermittent installation can be increased by connecting an additional high Mach number tunnel in parallel with a large transonic and lower supersonic range facility. Since at high Mach numbers relatively large models can be used, the high Mach number tunnel can be smaller; the maximum running

time of this tunnel would be larger than that of the main facility and, with the pressure drive, its Reynolds number could be increased.

Last but not least, it should be noted that by the same token much smaller, continuous wind tunnels can be operated in conjunction with a large intermittent installation. For example, the 6-ft. tunnel vacuum drive considered above would be suitable to run continuously a supersonic wind tunnel of approximately 1·5 ft. square working section. Such small auxiliary tunnels are useful for carrying out fundamental or specialised tests including heat transfer and hypersonic flow problems.

The foregoing are some of the worthwhile features characteristic of intermittent wind tunnel installations.

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The Uses of the ACE Computor

by

E. T. GOODWIN, M.A., Ph.D.
(National Physical Laboratory, Teddington, Middlesex)

WHEN I accepted the invitation to give a lecture on "The Uses of the ACE Computor" my first thought was to ask for the title to be corrected. The "ACE" as such has yet to be built and the machine that has been in use in the Mathematics Division of the National Physical Laboratory is a pilot model. However, to an audience whose chief interest is in aeronautics, the ambiguity of a title including the phrase "Pilot ACE" probably outweighs the advantage of its accuracy.

As its name implies, the Pilot ACE was built, at the N.P.L., with the intention of testing out the practicability of various ideas in the design of a full scale automatic computing engine, or ACE as it was called. The over-riding consideration was economy of equipment but, despite the rudimentary nature of the facilities provided on the machine, it was found to be a fast and powerful computor and has been fully and successfully employed for the past three years on a 13 hour basis.

Before considering the uses to which the machine has been put it may be as well to give a short description of it.

Figure 1 gives a general view of the machine. The "string and sealing wax" appearance which betokens construction in a laboratory can easily be recognised. It is a serial binary machine and its high speed store consists of eleven acoustic delay lines each holding 32 words, that is numbers or instructions, of 32 binary digits each. It happens that two are visible on the right of this figure, although they are normally housed in the temperature-controlled box behind the machine. The input and output of the machine is by means of punched cards, the card reader and punch being situated on the far side of the control panel. Fig. 2 gives a view of the machine from this end.

For over two years we only had the very limited store already referred to. Our experience in this period shows clearly that the smallness of the store need not prohibit the effective use of a machine, provided that the input and output system is good, although it also reflects great credit on the men who devised the programmes which we have used. Now, however, the position has been greatly eased by the addition of a magnetic drum store carrying 128 tracks, each the equivalent of one delay line, that is, 4,096 words in all; Fig. 3 gives a close up view of the magnetic drum. This drum is of an interesting and unconventional design. Instead of a full complement of 128 reading and 128 writing heads there are only 16 of each but these are equipped with a head-shifting device which moves them to any one of 8 positions. This arrangement, which has proved very successful, results in a considerable economy in associated electronic equipment.

One difficulty in discussing the uses of a general purpose digital computor has been very well put by Dr. Wilkes, when he said that asking whether these machines can do this or that problem is tantamount to asking whether they can do arithmetic, the answer being that they can. Any problem for which a computational method can be devised can then be solved but, of course, the time to do so might well be prohibitive even allowing for the high speed of these machines, and the pilot ACE multiplies in a five-hundredth of a second and adds in a thirty-thousandth. Therefore this paper contains merely some details of representative problems on which the machine happens to have been employed.

Historically, one of the first problems solved on this machine was ray tracing through a complex lens system. Indeed this was the problem put on the machine at its first press show, with the result that one paper described the working part of the machine as "consisting of a complicated lens system"! Simple algebraic equations have to be solved for each refracting surface and, for example, in a problem we have on hand at present it is required to find the effect of changes in radii, thickness of elements, distance between elements and refractive indices for a lens system with twenty-two surfaces. This particular lens is required for survey work and provides a link with another regular commitment, the solution of stereograms, arising from aerial surveys, in which sets of simultaneous algebraic equations are solved by an iterative process.

Both these are examples of what individually are fairly small jobs. Some of the largest jobs, the physical background of which cannot be divulged, have consisted in the computation of complicated mathematical functions which are the elements of fairly large determinants of which the zeros have to be found. It is interesting to observe that success in this work hinged on shrewdness in estimating from previous results where these zeros would lie—we are still not entirely mechanised!

The field in which the greatest amount of systematic work has been done is undoubtedly that of linear algebra, that is, manipulations with matrices, the solution of algebraic linear simultaneous equations and the determination of latent roots. This is partly fortuitous in the sense that the Aircraft Industry which, needless to say, has a large number of this type of job, is the first to have been interested in using our machines either directly or through the Royal Aircraft Establishment. On the other hand, it truly reflects the fact that this is a type of work for which these machines are particularly well suited. Some of this work has been on problems of stress analysis but the majority has been connected with the perennial problem of flutter. Of the three stages of the flutter problem we have usually done the first two, computing the normal modes and setting up the flutter determinant, which has then been solved on the R.A.E. simulator, although occasionally we have done this stage as well (when accurate results are required, as we tell

*A Section Lecture delivered on 16th November 1954.

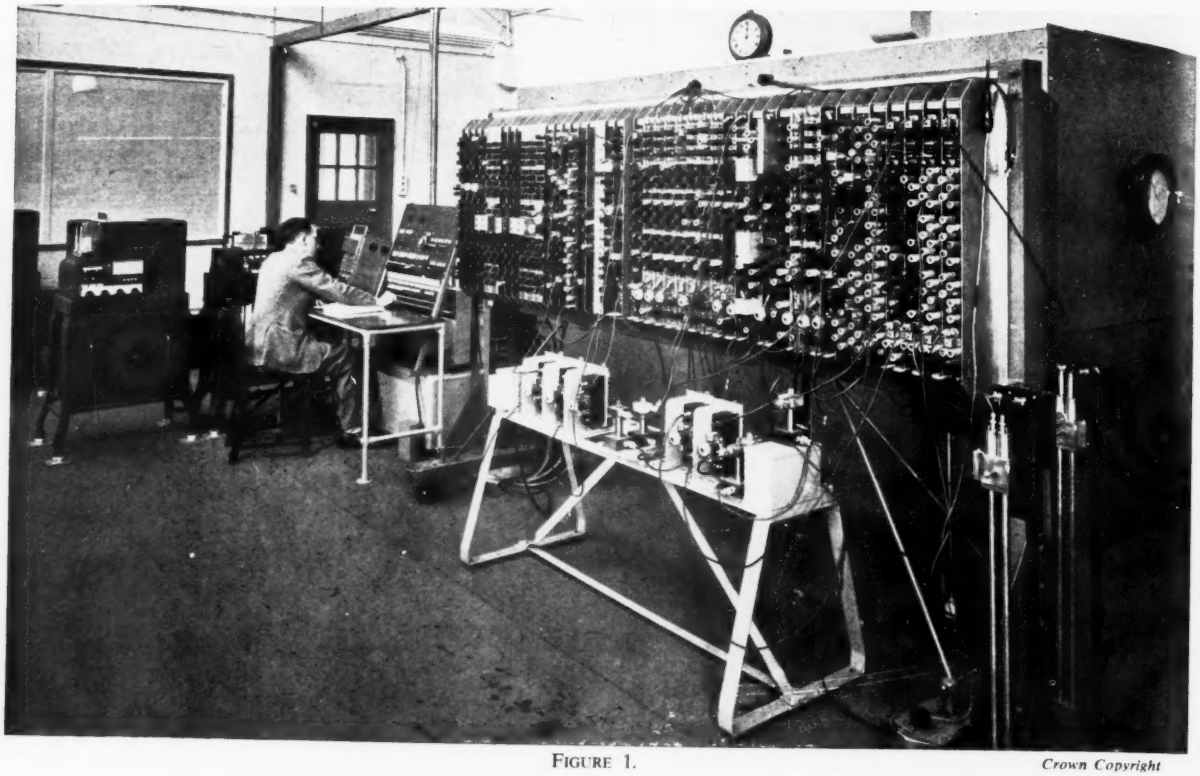

FIGURE 1. *Crown Copyright*

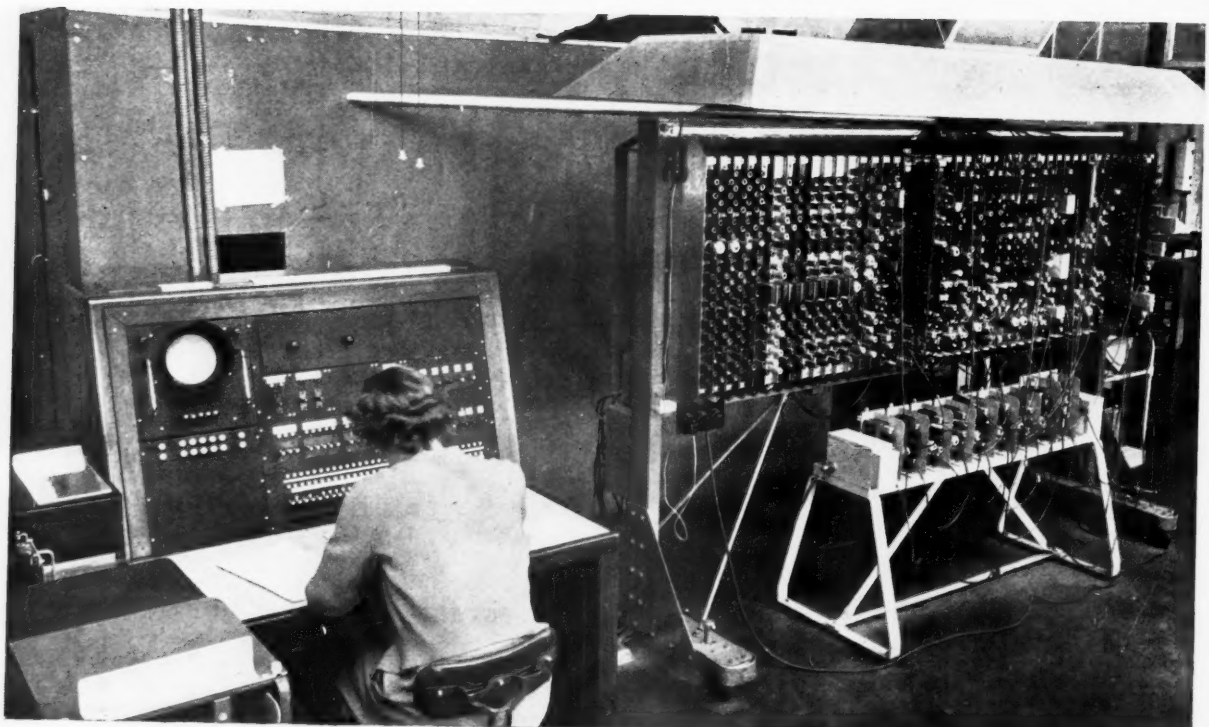

FIGURE 2. *Crown Copyright*

R.A.E.!). We have also done a good deal of work for one firm which requires to have not merely the flutter speeds but damping curves for velocities and mass-balance ratios near the critical values. Another case when the digital machine is needed is for the final stage for more than six degrees of freedom.

A large scale statistical job which R.A.E. staff have recently carried out on our machine is the determination of auto-correlation coefficients for the vast quantity of strain-gauge readings amassed during the recent Comet investigation trials. This work involved eight million multiplications, and these constituted a mere ten per cent. of all the operations that had to be made on the machine. Another statistical job has been a joint enterprise with the Road Research Laboratory on the optimum timing of traffic signals, given various conditions of traffic flow.

A large number of problems have involved the solution of ordinary differential equations, both linear and non-linear. The trajectories of all kinds of missiles are of this type. The machine is particularly effective in solving such problems when random effects are introduced; effective, that is, relative to a human computer who, if a good one, is demoralised by the absence of satisfactory checks and, if a bad one, is bad anyhow.

Another form of tracking problem that has afforded us a large amount of work consists of the calculation of orbits in the new proton-synchrotron being designed for the European Council for Nuclear Research. This machine will be a quarter of a mile in circumference and a particle while being accelerated should encircle it a million times. It is hoped to restrict the diameter of the tube to about two inches so that the particles have to be kept within a two inch tube for a journey as far as from here to the moon. Very slight misalignments in the magnets can seriously affect the possibility of doing this and the problem has been to solve simple non-linear differential equations subject to large numbers of different sets of random perturbations.

A problem concerned with the stresses set up in the launching equipment when aircraft are launched from a carrier has involved the solution of twenty-two simultaneous second-order non-linear differential equations having discontinuous coefficients. In this case the boundary conditions were specified partly at one end and partly at the other end of the range of integrations, a situation which calls for a completely different method of solution from that used in the "one-point boundary condition" case.

Integral and integro-differential equations have also been solved on the pilot ACE, the latter in connection with nuclear scattering problems. In each case a direct finite difference method has been used, which effectively reduces the problems to linear algebra.

While the selection of problems given here has shown that the pilot ACE really is a very general-purpose computor, there is one very important omission. There is no reference to partial differential equations. This is a convenient place to make some general remarks on our work so far and our hopes for the future.

Although some partial differential equations have in fact been solved, we have not made any systematic

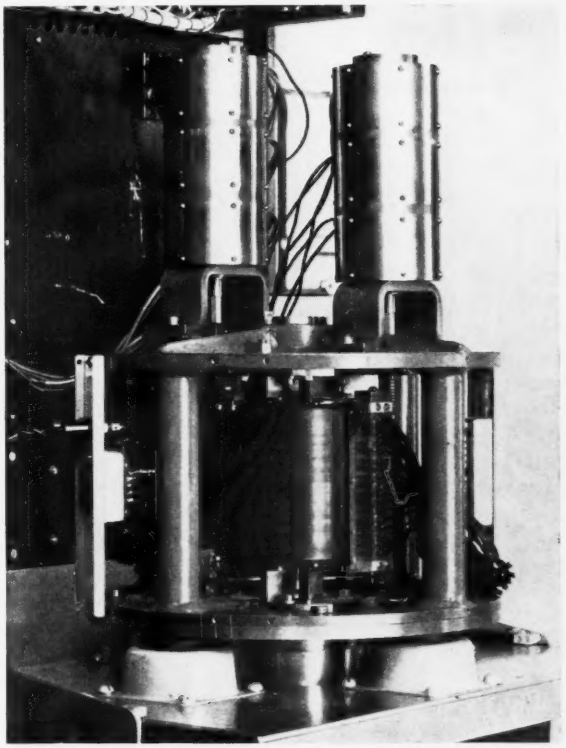

FIGURE 3. *Crown Copyright*

attack on the general subject simply because we have not had time, and we have not had time because we have been kept very busy doing the types of problems described earlier. In particular we have been kept very busy with problems of interest to the Aircraft Industry. But periodically someone asks what use is being made of these machines in aerodynamical research problems and the answer so far has been "precious little." Moreover, aerodynamical problems, the unsolved ones, are likely to be particularly intractable.

It is highly desirable that we should put the same degree of effort into devising methods for the solution of partial differential equations as we have into problems of linear algebra. Indeed, in view of the much greater complexity of the problem, a much greater effort is needed.

The moral seems clear. It is the duty of an establishment such as the Mathematics Division, N.P.L., to be in the forefront of such work as the exploitation of high-speed digital computors. We must therefore devote a good deal more of our time to research and this, inevitably, must be at the expense of the computing service which we provide. In the next year or so you can expect a distinct hardening in our attitude to outside jobs that require extensive planning or programming. However, other machines will soon be available, firms will be getting their own machines, and a good deal of our work has now become sufficiently standardised for us to continue to take it on without taking up the time of any of our research staff on it. But if we are found reluctant to undertake some new programme of work it is simply because we are trying to think of the future.

Ninetieth Annual Report of the Council 1954-1955

THE OUTSTANDING event of the past Session has been the Tenth British Commonwealth and Empire Lecture which was delivered by His Royal Highness the Duke of Edinburgh in Church House, Westminster, on 16th December 1954. The attendance was over 800—a record attendance for a Society Lecture.

The number of members continues to increase satisfactorily; the first Examinations for Part I of the Revised Associate Fellowship Examination Regulations have been held; the attendance at both Main and Section Lectures has been good.

Yet another Memorial Lecture has been established—the Cayley Memorial Lecture at Brough—and with the Mitchell (Southampton), the Pierson (Weybridge) and the Barnwell (Bristol), the total number of such Lectures is now four. The establishment of a Memorial Lecture by a Branch is proving to be an excellent innovation, and is the most important function in the Branch Calendar of Lectures.

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Election of President and Vice - Presidents

Sir Sydney Camm, C.B.E., F.R.Ae.S., was elected President for 1954/55 and took office at the Eighty-Ninth Annual General Meeting held on 6th May 1954.

At the Meeting of Council held on 3rd June 1954, the following were elected Vice-Presidents:

Mr. G. R. Edwards, C.B.E., B.Sc., F.R.Ae.S.

Mr. A. G. Elliott, C.B.E., F.R.S.A., M.S.A.E., M.I.Mech.E., F.R.Ae.S.

Mr. P. G. Masefield, M.A., F.I.A.S., F.R.Ae.S.

At the meeting of Council held on 30th September 1954, Mr. N. E. Rowe, C.B.E., B.Sc., D.I.C., F.C.G.I., F.I.A.S., F.R.Ae.S., was elected President-elect of the Society.

Fellowship of the Society

At the Eighty-Ninth Annual General Meeting, held on 6th May 1954, it was announced that the following had been elected Fellows:

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		R. H. Woodall

Lectures

The following Main Lectures and Section Lectures have been read before the Society in 1954/55:

1954

12th October: SECTION LECTURE—Behaviour of Light Alloys at Elevated Temperatures, E. R. Gadd, F.I.M.

21st October: MAIN LECTURE—The Development of Re-Heat, J. L. Edwards, A.F.R.Ae.S.

2nd November: SECTION LECTURE—Design of Small Jet Engines, H. S. Rainbow.

4th November: MAIN LECTURE AT THE BROUGH BRANCH—The First Cayley Memorial Lecture—"Sir George Cayley, Bart.—The Father of British Aeronautics," Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S.

11th November: MAIN LECTURE—Boundary Layer Control, Dr. G. V. Lachmann, F.R.Ae.S.

16th November: SECTION LECTURE—Uses of the "ACE" Computer, Dr. E. T. Goodwin.

25th November: LECTURE—The Development and Investigation of Fatigue Cracks, Dr. N. Thompson, B.Sc.

9th December: SECTION LECTURE—Problems of Structural Design, D. James, B.Sc., A.F.R.Ae.S.

16th December: MAIN LECTURE—The Tenth British Commonwealth and Empire Lecture—Aviation and the Development of Remote Areas, His Royal Highness the Duke of Edinburgh, K.G., K.T.

21st December: SECTION LECTURE—Servo Tab Controls, Dr. W. J. Strang, A.F.R.Ae.S.

1955

4th January: SECTION LECTURE—Recent Advances in the Knowledge of Transonic Air Flow, C. H. E. Warren, M.A., A.F.R.Ae.S.

6th January: MAIN LECTURE—Lecture to Young People—Great Events in Aviation, P. G. Masefield, M.A.(Eng.), F.I.A.S., F.R.Ae.S.

18th January: SECTION LECTURE—Manufacture of Integral Structures, Dr. E. G. West, Ph.D., B.Sc.

27th January: SECTION LECTURE—Dynamic Problems of Interplanetary Flight, D. F. Lawden, M.A.

8th February: SECTION LECTURE—Some Trends in the Development of Aircraft Electrical and Starting Systems, R. H. Woodall, F.R.Ae.S.

10th February: MAIN LECTURE AT THE ISLE OF WIGHT BRANCH—Prospects and Problems of Rocket Propulsion for Aircraft, Professor A. D. Baxter, M.Eng., F.R.Ae.S.

17th February—SECTION LECTURE—Problems Associated with Stress Concentration, H. L. Cox, M.A., F.R.Ae.S.

1st March: SECTION LECTURE—The Scientific Approach and Research in Aircraft Production, Professor J. V. Connolly, B.Eng., F.R.Ae.S.

10th March: MAIN LECTURE AT PRESTON BRANCH—Structural Safety, Professor A. G. Pugsley, O.B.E., D.Sc., F.R.Ae.S.

15th March: SECTION LECTURE—The Production of Large Forgings, C. Smith, F.I.M., and J. Crowther, M.Sc., F.I.M.

17th March: MAIN LECTURE—The Eighth Louis Bleriot Lecture—Making Aeroplanes Independent of Runways, Monsieur Georges Hereil, President, Director-General, S.N.C.A.S.E.

24th March: MAIN LECTURE—Analogue Computing Applied to Aeronautical Problems, K. V. Diprose, B.A.

31st March: SECTION LECTURE—Application of Aerial Survey to the Economic Development of a Country, T. D. Weatherhead, O.B.E., M.A.

The following Lectures will complete the Programme:

14th April: MAIN LECTURE AT GLASGOW BRANCH—Mixed Power Units in Modern Aircraft, M. J. Brennan, B.Sc., F.R.Ae.S.

19th April: SECTION LECTURE—Thermoelasticity, Professor W. S. Hemp, M.A., F.R.Ae.S.

21st April: MAIN LECTURE—Aeronautical Research in Sweden, Bo K. O. Lundberg, F.I.A.S., F.R.Ae.S.

26th April: SECTION LECTURE—Aerial Systems for Aircraft, R. A. Burberry.

3rd May: SECTION LECTURE—Plastic Structures, G. C. Hulbert, B.Sc.

19th May: MAIN LECTURE—The 43rd Wilbur Wright Memorial Lecture—Flight Control, Dr. C. S. Draper.

Divisions

As a result of the Report of the *Ad Hoc* Committee, which had been set up to investigate how the Society could best help the Divisions and Branches overseas, the Council decided to send the Secretary to visit, in turn, South Africa, Australia, New Zealand and Singapore. This he did during August and September 1954.

During his tour the Secretary met the Council of each Division, and the Committee of each Branch. Many discussions were held and the resulting knowledge and insight into local problems will inevitably benefit the relationships with the Divisions by increased understanding.

Throughout the Commonwealth there is an enthusiasm for the use of the aeroplane as distinct from its design and manufacture, and upon such enthusiasm the well-being of the Divisions rests. This is best exemplified in the New Zealand Division, upon whose Council serve many of the best known figures in New Zealand Aviation.

The Secretary visited many places of aeronautical interest; the list is lengthy and comprises:

10 Aircraft firms making or repairing aeroplanes.

7 Airline Operators.

5 Research Establishments.

5 Air Force Stations (R.A.F., R.A.A.F., and R.N.Z.A.F.).

4 Flying Clubs.

3 Operators, other than Airlines.

2 Airports under construction.

In addition, he gave eleven talks and lectures, two radio interviews, and a radio talk.

To enable such a programme to be fulfilled in less than seven weeks the organisation of each had to be extremely efficient; everything went according to plan. It is impossible to enumerate all the many people who made memorable the Secretary's tour, but the Council would like to extend their appreciative thanks to the Council of each Division, and the Committee of each Branch for the ready welcome which was given to the Secretary, and for their unselfish efforts in forwarding the work of the Society throughout the Commonwealth. The Council recognise the great value of the work done by the Secretaries, and would like to thank particularly Air Commodore J. H. C. Wake (Southern Africa), Mr. W. Isbister (Australia), Mr. T. T. N. Coleridge (New Zealand), and Mr. A. M. Lovatt (Singapore), for the way in which the Society is flourishing under their unceasing care. To them all credit!

As in this country, so throughout the Divisions, there is much help given which is hidden, or unobtrusive; many firms provide facilities in the way of lecture room accommodation, and to these also the Council tender their thanks.

Branches

Since the last Annual Report there have been no new Branches formed and the number therefore remains at twenty-five.

During the Session another Memorial Lecture has been instituted, the Sir George Cayley Memorial Lecture of the Brough Branch. This Lecture was classed as a Main Lecture and supplemented the normal Main Lectures at Branches; these were held at the Isle of Wight, Preston and Glasgow Branches.

Although there have been few outstanding features in the work of the Branches during the past year, the Branches have continued their activities with their usual zeal. The standard of the Lectures given before the Branches remains extremely high, resulting in good attendances of Members.

The Branches Conference, which is held biannually, continues to be a success, when representatives from each Branch meet and are able to talk over their Branch affairs.

Much of the success of the Branches is due to the enthusiasm of the Honorary Secretaries and the Chairmen, and the Council take this opportunity of thanking them for the consistent effort which is made. The organisation of every function is first class.

Firms, closely related to the Branches, have given much unadvertised assistance, and that with good-will; this the Council realise, and would like to tell these organisations their thanks.

Membership

There has been a steady increase over the year, and again the total increase amounts to about 200.

The table on page 286 shows, in detail, the Membership on 31st December 1954.

The increase is almost entirely in the grade of Associate Fellow, and, in general, is brought about by the upgrading of Graduates and Associates. The Graduate and Student memberships are approximately the same as during the previous year, being kept to this level by an inflow of new members.

Graduates' and Students' Section

The policy of the Committee has been to encourage Graduates and Students to present papers, and this year four lectures have been read by the Members of the Section. This policy will be continued, for the Committee have been heartened by its success during the past year.

The average attendance at the nine meetings held during the year has been 65; this is the best in recent years, for in 1953/54 it was 47, and in 1952/53 it was 53. The attendances at two of the meetings were 130 and 140 respectively, being record attendances for meetings of the Section.

The Committee's aim is to provide lectures covering the broader aspects of aviation rather than on the more specialised subjects, which are best suited as Section Lectures.

In addition to the nine meetings and five visits arranged during the year, a Reception and Dance was

again held in the Society's offices. The attendance, lower than in previous years, was disappointing, but the Reception was considered to be the most successful yet held. It is hoped that this function will become an annual event, and will receive the full support of the Members of the Section.

The Committee has submitted proposals for the production of a booklet which sets out the many careers open to the Graduate in the expanding field of aeronautics. This will receive the consideration of the Council.

LIST OF MEETINGS DURING 1954/55

25th March 1954: Airworthiness Requirements for Take-Off and Landing, by L. J. W. Hall, D.C.Ae., Grad.R.Ae.S.

29th April: Fuselage Structural Design Methods, by R. J. Jupe, Grad.R.Ae.S.

30th September: Air-to-Air Photography, by Russell Adams, F.R.P.S.

19th October: The Propeller-Turbine in Airline Service, by T. M. Corson, D.C.Ae., Grad.R.Ae.S.

4th November: Film—The German A4 Rocket Commentary, by K. W. Gatland, F.R.A.S.

17th November: Bird Flight and the Aeroplane, by Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S.

2nd December: Seaplanes—a Survey of the Development of Water-Based Aircraft Design, by R. F. R. Storey, B.Sc., Stud.R.Ae.S.

25th January 1955: Test-Flying a V-Bomber, by Squadron Leader H. G. Hazelden, D.F.C. and bar, and R. H. Williams, B.Sc., A.F.R.Ae.S.

15th February: Is Postgraduate Study Abroad Worthwhile?—Discussion. Chairman: Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S.

LIST OF VISITS DURING 1954/55

26th June 1954: Uxbridge Air Traffic Control Centre.
17th July: National Physical Laboratory, Teddington.
18th September: Evening River Tour of London Docks.
13th October: Weekday visit to the Royal Aircraft Establishment.
19th February 1955: Guinness's Brewery, Park Royal.
30th April: Vickers-Armstrongs Ltd., Weybridge.
21st May: Hawker Aircraft Ltd.

Honours Awarded to Members

Members of the Society have been honoured by Her Majesty the Queen during the year. These the Council have much pleasure in congratulating.

Other Honours have been conferred upon Members of the Society by learned Societies and other bodies; the Council also congratulate these recipients.

BIRTHDAY HONOURS LIST 1954

Knight Bachelor—A. A. Hall (*Fellow*).

Knight Commander of the Bath—Air Marshal Sir John Boothman (*Associate Fellow*).

Companion of the Order of St. Michael and St. George—I. Bowen (*Fellow*).

Commander of the Order of the British Empire—A. E. Russell (*Fellow*).
Wing Commander R. Milroy Hayes (*Associate*).

Officer of the Order of the British Empire—F. A. Foord (*Fellow*).

Member of the Order of the British Empire—M. L. Burgan (Awarded the R. P. Alston Memorial Prize 1954).

NEW YEAR HONOURS LIST 1955

Knight Bachelor—Rear-Admiral M. S. Slattery (*Fellow*).

Companion of the Order of the Bath—W. R. McGaw (*Fellow*).

Commanders of the Order of the British Empire—B. Lampard-Vachell (*Associate Fellow*).
Professor G. Temple (*Fellow*).

Officers of the Order of the British Empire—Professor L. Howarth (*Fellow*)
E. L. Ripley (*Associate Fellow*).
W. H. Yoxall (*Associate Fellow*).

Member of the Order of the British Empire—S. A. Cooper (*Associate*).

BRITISH AIRLINE PILOTS' ASSOCIATION

Captain T. H. Farnsworth (*Associate Fellow*) has been awarded the British Airline Pilots' Association first Gold Medal.

MEMBERSHIP AT 31st DECEMBER 1954

Grade	London Register	Australian Division	New Zealand Division	Southern Africa Division	Life and Honorary	Totals	Suspended Members (included in the foregoing figures)
Fellows	370 (359)	10 (11)	— (—)	1 (1)	52 (53)	433 (424)	6 (5)
Associate Fellows	3,193 (2,997)	114 (106)	29 (28)	42 (38)	17 (16)	3,395 (3,185)	71 (57)
Associates ..	1,934 (1,948)	69 (75)	59 (64)	76 (74)	5 (5)	2,143 (2,166)	107 (125)
Graduates ..	1,213 (1,213)	60 (50)	6 (7)	5 (6)	— (—)	1,284 (1,276)	42 (42)
Students	737 (743)	45 (53)	5 (1)	9 (8)	— (—)	796 (805)	46 (56)
Founder Members	14 (14)	— (—)	— (—)	— (—)	1 (1)	15 (15)	— (—)
Companions ..	149 (151)	7 (6)	4 (4)	4 (3)	10 (10)	174 (174)	6 (15)
Temporary Honorary Members	— (—)	— (—)	— (—)	— (—)	48 (45)	48 (45)	— (—)
	7,610 (7,425)	305 (301)	103 (104)	137 (130)	133 (130)	8,288 (8,090)	278 (300)

(Figures in brackets are corresponding figures at 31st December 1953)

INSTITUTE OF METALS

Major P. L. Teed (*Fellow*) has been elected Vice-President of the Institute of Metals.

Dr. L. Aitchison (*Fellow*) has been awarded the Platinum Medal of the Institute of Metals for his services "in industry, education, and the public service."

THE INSTITUTE OF THE AERONAUTICAL SCIENCES

Sir William S. Farren (*Fellow*), President of the Society 1953/54, has been awarded an Honorary Fellowship of the Institute of the Aeronautical Sciences, for his contribution to the advancement of Aeronautics.

Major D. Lester Gardner (*Honorary Fellow*) and Sir Richard Southwell (*Fellow*) have also been elected Honorary Fellows of the Institute of the Aeronautical Sciences.

Mr. N. E. Rowe (*Fellow*), Member of Council and President-elect, Mr. L. P. Coombes (*Fellow*), Professor Maurice Roy (*Fellow*) and Dr. William Jones (*Fellow*) have been awarded Fellowships of the Institute of the Aeronautical Sciences.

Mr. Z. M. Ciolkosz (*Associate Fellow*) has been awarded the Wright Brothers' Medal, jointly with Mr. D. N. Meyers, by the Institute of the Aeronautical Sciences, for their paper on "Matching the Characteristics of Helicopters and Shaft Turbines."

Dr. Theodore von Kármàn (*Honorary Fellow*) has been awarded the Wright Brothers' Memorial Trophy (awarded for public service of enduring value to aviation in the United States) for his "outstanding achievements in supersonic research and jet propulsion."

INSTITUTION OF MECHANICAL ENGINEERS

Mr. H. G. Conway (*Fellow*) and Mr. E. G. Collinson (*Associate Fellow*) have been awarded jointly the Water Arbitration Prize by the Institution of Mechanical Engineers for their paper "An Introduction to Hydraulic Mechanism Theory."

THE ROYAL SOCIETY

Professor A. J. Sutton Pippard (*Fellow*) has been elected a Fellow of the Royal Society.

UNIVERSITY OF BIRMINGHAM

Sir Harold Roxbee Cox (*Fellow*), Past President of the Society, has been awarded the Honorary Degree of Doctor of Science by the University of Birmingham.

CANADIAN AERONAUTICAL INSTITUTE

Dr. J. J. Green (*Fellow*) has been elected the first President of the Canadian Aeronautical Institute and Mr. H. C. Luttman (*Associate Fellow*) has been appointed Secretary.

Mr. G. H. Dowty (*Fellow*) has been elected an Honorary Fellow of the Canadian Aeronautical Institute.

INSTITUTION OF CIVIL ENGINEERS

Professor A. J. Sutton Pippard (*Fellow*) has been elected Vice-President of the Institution of Civil Engineers for the year 1954/55.

QUEEN'S UNIVERSITY, BELFAST

Rear Admiral Sir Matthew M. S. Slattery, C.B. (*Fellow*) has received the Honorary Degree of Doctor of Science from the Queen's University, Belfast.

COLUMBIA UNIVERSITY, U.S.A.

A. D. Barber (*Graduate*) has been awarded a King George VI Memorial Fellowship, tenable at Columbia University, U.S.A.

SENATE OF THE UNIVERSITY OF LONDON

Dr. W. F. Hilton (*Fellow*) has been awarded by the University of London, the degree of Doctor of Science for his work in the field of aerodynamics.

FEDERATION AERONAUTIQUE INTERNATIONALE

Captain K. J. G. Bartlett (*Associate Fellow*) has been elected President of the Fédération Aéronautique Internationale.

The Fédération Aéronautique Internationale has awarded a de la Vaux Medaille to Squadron Leader N. F. Duke (*Associate*). These medals are awarded to holders of recognised world records gained during the year.

The Fédération Aéronautique Internationale has also awarded Paul Tissandier Diplomas to Sir Sydney Camm (*Fellow*), President; Mr. A. G. Elliott (*Fellow*), Vice-President; Mr. W. E. W. Petter (*Fellow*) and Mr. J. Smith (*Fellow*). These diplomas are awarded to those who have "by their influence, work, initiative and devotion, or in some other way, served the cause of aviation in general, especially private and sporting flying."

ROYAL SOCIETY OF ARTS

Wing Commander T. R. Cave-Brown-Cave (*Fellow*) has been awarded a prize by the Royal Society of Arts in their Bicentenary Competition for forecasts of practical aspects of life on earth in the year 2000 A.D. He submitted a scheme for Rooftop Roadways.

FREEDOM OF THE BOROUGH OF CHELTENHAM

Mr. G. H. Dowty (*Fellow*) has been awarded the Honorary Freedom of the Borough of Cheltenham in recognition of the outstanding and distinguished services rendered by him in the field of industry and to the progress and life of the town over many years.

INSTITUTE OF NAVIGATION

Captain A. M. A. Majendie (*Associate Fellow*) has been awarded the Gold Medal of the Institute of Navigation for his contributions to the navigation of jet aircraft.

LA LEGION D'HONNEUR

Professor Maurice Roy (*Fellow*) has been made a Commander in the Order of La Legion d'Honneur for his services to aviation.

Medals and Awards of the Society

Full particulars of the Medals and Awards of the Society were published in the August 1954 issue of the Journal.

JOURNAL PREMIUM AWARDS

A list of Premium Awards made for 1953 was published in the August 1954 issue of the Journal of the Society.

BUSK MEMORIAL SCHOLARSHIP

The Busk Memorial Scholarship was awarded to Mr. C. G. Plane for the continuance of his post-graduate research at Queen Mary College, London.

ROYAL AERONAUTICAL SOCIETY CHARTER SCHOLARSHIP

The Charter Scholarship for 1954/55 was awarded to Mr. J. Waters for a second year to allow him to continue his post-graduate course at Imperial College of Science and Technology.

GEOFFREY DE HAVILLAND MEMORIAL SCHOLARSHIP

The Geoffrey de Havilland Memorial Scholarship for 1954/55 was awarded to Mr. N. Birch to enable him to take a course at the College of Aeronautics at Cranfield.

SOCIETY OF BRITISH AIRCRAFT CONSTRUCTORS' EDUCATIONAL GRANTS

The following were awarded Educational Grants by the Society of British Aircraft Constructors at a Selection Committee Meeting held in the offices of the Royal Aeronautical Society on 26th July 1954:

M. D. Chamberlain, Spalding Road, Pinchbeck, Spalding, Lincs. To serve his apprenticeship with the de Havilland Engine Co. Ltd.

B. J. Fines, Wingland, Sutton Bridge, near Spalding, Lincs. To serve his apprenticeship with the de Havilland Aircraft Co. Ltd.

R. F. H. Owston, 20 Ashlea Drive, Giffnock, Glasgow. To serve his apprenticeship with the de Havilland Aircraft Co. Ltd.

A. E. Pryce, 6 Bryn Avenue, Rhos-on-Sea, Colwyn Bay. To serve his apprenticeship with the de Havilland Aircraft Co. Ltd.

R. de Saeger, 269 Battle Road, Hollington, St. Leonards-on-Sea.

The Scholarship Selection Board consisted of representatives of the Society of British Aircraft Constructors and of the Royal Aeronautical Society.

ELLIOTT MEMORIAL PRIZE

The Elliott Memorial Prize has been awarded to the following, who obtained the highest marks in the General Studies Examination at Halton:

Flight Sgt. Apprentice T. E. Enright (May 1951 Entry).

Sgt. Aircraft Apprentice E. J. Walter (Sept. 1951 Entry).

Finance

The Income and Expenditure Accounts and Balance Sheets of The Royal Aeronautical Society and the Aeronautical Trusts Limited for 1954 are published on pp. 290-303.

Donations

Donations have been received during 1954 from the following:

Blackburn and General Aircraft Limited.
Bristol Aeroplane Company Limited.
de Havilland Aircraft Company Limited.
Dowty Equipment Limited.
English Electric Group of Companies.
Folland Aircraft Limited.
Hunting Percival Aircraft Limited.
Sir Frederick Handley Page.
Rolls-Royce Limited.
Society of British Aircraft Constructors.
Ministry of Supply.
Vickers-Armstrongs Limited.
Westland Aircraft Limited.

The Society has also received grants from the Society of British Aircraft Constructors and the Ministry of Supply for technical work.

Garden Party

A report of the Garden Party held at London Airport on 13th June 1954 was published in the August 1954 issue of the Journal of the Society.

Like most outdoor functions during the past year, the Garden Party suffered from the bad weather, but, despite the rain, the President and Lady Camm had the pleasure of welcoming many guests.

Library

The number of acquisitions was slightly higher than the previous year—265 as against 237—but this was largely due to the purchase of several books on Physics with the object of bringing this section up to date. There was a drop of 45 loans on the 1953 figure of 1,005 and the 1954 figure of 960 was six less than the 1952 figure. It would seem that 950 is about the number of loans that can be expected each year. Good use continues to be made of the telephone enquiry service by both members and others.

The photograph and slide collections have been augmented and requests for the service have been steady throughout the year, although, of course, the demand for slides is heavier in the winter.

The re-cataloguing of the Library has been carried on without any disruption in the service. It should be completed during 1955.

A little historical material has been presented, but it cannot be over-emphasised that the Library is always interested in acquiring old papers, journals, photographs, books and any other material dealing with the early days of flight.

Publications

The Journal has continued to make progress; as a result of the increase in membership of the Society and additional subscriptions, more copies than ever have been printed in 1954. The number of papers submitted for publication has increased, and more have been received from overseas.

Because a number of complaints had been received from overseas members that their Journals were arriving in poor condition, experiments with wrappers were made for some months. Postcards, asking for comments on Journals sent "flat in an envelope" or "rolled and wrapped" were enclosed with the overseas copies. Although approximately 2,000 copies of the Journal

were sent each month only about 400 replies were received; the opinions expressed on them were so evenly divided that a clear decision on this vexed question was impossible. A number of members sent helpful suggestions and samples of envelopes and coverings used on other periodicals. Unfortunately the ideal solution would add greatly to Journal costs, but experiments and enquiries are continuing, and in 1955 it is proposed to send out for a trial period all Journals, both home and abroad, in wrappers.

In February 1954 the Council agreed that the *Aeronautical Quarterly* should revert to four issues a year and that a volume be complete in one calendar year. To accomplish this, five numbers—Part 4 of Volume IV and Parts 1 to 4 of Volume V—have been published between February and December 1954. Beginning with Volume VI in 1955 the *Quarterly* will be published in February, May, August and November each year. Papers are now being published six to nine months after they are accepted for publication.

From Volume V the subscription to the *Quarterly* for non-members of the Society was increased from £2 1s. 0d. to £3 1s. 0d., including postage and packing. Prices for members remain unchanged.

The fourth Monograph sponsored by the Society, "Massbalancing of Aircraft Control Surfaces," by H. Templeton, was published in November 1954 and has been well received. The other three Monographs: "The Properties of Metallic Materials at Low Temperatures," by P. L. Teed, "The Structures and Mechanical Properties of Metals," by Dr. Bruce Chalmers (both of which have run to second printings), and "Adhesives for Wood," by R. A. G. Knight, have continued to sell. Several more Monographs are in hand and it is hoped that one Monograph and possibly two text books will be published in 1955.

At the beginning of the year Miss E. C. Pike became the Technical Editor of the Society's Publications.

The Journal has now been running in its new format for two years, and it has proved a most successful change. It is not unknown for the Editor to receive a letter containing complimentary remarks both for the Journal format and for its contents.

That the Journal is maintaining its high standard is due largely to the Editor and her staff, who have worked exceedingly hard to this end. Council, on behalf of all the members of the Society, acknowledge a task well done, and congratulate the Editor on the success attending her efforts.

The Fifth Anglo-American Aeronautical Conference

The Conference will be held in Los Angeles from 20th June to 1st July 1955 and arrangements are now well in hand. There will be a record attendance of British representatives, for more than one hundred and twenty registrations have been made.

It would appear that this Conference will be no less successful than those of past years, for the response has been very good indeed, and everyone—both American and British—is looking forward to Los Angeles with much pleasure.

Officers and Committees

Once again the Council would thank the Members of the various Committees for their continuing helpful guidance; indeed, not a Meeting of Council passes but there are some recommendations from one or more Committees to be discussed. These recommendations are the result of much thought and consideration by the Committees. That this is so is appreciated by the Council, and to the Members of the Committees the Council render the thanks which are their due.

Technical

New issues of both Structures and Aerodynamics Data Sheets have been made during the year. Twenty-four new Structures Data Sheets have already been circulated to all subscribers, and in this set are sheets which are applicable directly to the development of integral panel sections of optimum design. Fifty of the existing Structures Data Sheets have been reprinted.

In Aerodynamics, forty-one Data Sheets have been issued, covering the extension of the existing series to Supersonics. In the past, only complete sets of Data Sheets have been sold, individual copies or individual groups not being available. The Supersonics Data Sheets, however, have been made available as a separate unit, as well as being included in the complete sets of Aerodynamics Data Sheets.

The Aerodynamics Monograph covering the massbalancing of control systems is now on sale, and monographs or textbooks on aircraft stability, aircraft hydraulics, aircraft undercarriages, and instrumentation in testing aircraft, are being edited and should be published shortly. The existing monographs on materials continue to sell well.

TECHNICAL COMMITTEES

Aerodynamics Committee

Professor A. D. Young (*Chairman*)	Dr. D. W. Holder
Mr. M. Booth	Mr. R. Melling
Mr. P. J. Duncton	Mr. J. C. Stevenson
Mr. J. R. Ewans	Mr. H. H. B. M. Thomas
Mr. J. W. Fozard	Mr. A. K. Weaver

Performance Committee

Mr. Handel Davies (*Chairman*)	Mr. T. V. Somerville
Mr. W. J. D. Annand	Mr. C. F. Toms
Mr. S. R. Hughes	Mr. R. H. Whitby
	Mr. A. H. Yates

Structures Committee

Mr. D. James (*Chairman*)	Mr. E. Dixie Keen
Mr. H. L. Cox	Mr. K. L. C. Legg
Professor W. S. Hemp	Mr. F. Tyson
Mr. H. B. Howard	

The Council recognise the importance of the work of the Technical Committees, and thank the members for their continued effort in this field.

It can now be said that the position of the Data Sheets is as strong as ever, and for this excellent result much is due to the work of Mr. D. C. Smith, Head of the Technical Department, and his willing and able staff.

THE ROYAL

(INCORPORATED

BALANCE SHEET

1953 Figures £		£ s. d.	£ s. d.	£ s. d.
	Current Liabilities			
8125	Sundry Creditors		5542 6 3	
3783	Subscriptions and other amounts received in advance		4571 19 0	10114 5 3
	Surplus (Subject to depreciation of Investments)			
2000	*Reserve for Anglo-American Conferences*		3500 0 0	
	Income and Expenditure Account			
	Balance at 31st December 1953	13172 14 10		
	Add Surplus of Income over Expenditure			
13173	for year to date	1330 12 11	14503 7 9	18003 7 9
£27081				£28117 13 0

S. CAMM,
President.

G. P. BULMAN,
Honorary Treasurer.

REPORT OF THE AUDITORS TO THE MEMBERS

In our opinion and to the best of our information and according to the expenditure account of the Society together with the accounts of the Royal Aeronautical Trusts Limited give a true and fair view of the state of the Society's

We have obtained all the information and explanations which to the best Society has kept proper books of account and the above mentioned accounts are

3 Frederick's Place, Old Jewry, London, E.C.2.
22nd March 1955.

AERONAUTICAL SOCIETY

BY ROYAL CHARTER 1949)

31st DECEMBER 1954

1953 Figures £		£ s. d.	£ s. d.
	Current Assets		
1	Stock of Journals and other publications	1 0 0	
11661	Sundry Debtors	11098 7 2	
229	Payments in Advance	739 9 2	
6019	Cash at Bank and in Hand	5229 18 8	17068 15 0
7801	*Investments at Cost*		5600 0 0
	Market Value 31st December 1954: £5,355 (1953: £7,392)		
	Aeronautical Trusts Limited		
1	21 shares of 1/- each fully paid at cost	1 1 0	
1319	Amount due on current account	54 2 0	55 3 0
	Printed Books, Binding, Old Prints, etc.		
50	At nominal amount		50 0 0
	Nash Collection of Historical Aircraft		
—	At cost		5343 15 0
£27081			£28117 13 0

OF THE ROYAL AERONAUTICAL SOCIETY

explanations given to us, the above balance sheet and the annexed income and Aeronautical Society Endowment Fund included in the annexed accounts of affairs as at 31st December 1954 and of its surplus for the year ended on that date. of our knowledge and belief were necessary for our audit. In our opinion the in agreement therewith.

(*Signed*) PRICE WATERHOUSE & CO.

INCOME AND EXPENDITURE ACCOUNT

1953 Figures £			£ s. d.	£ s. d.
		To ESTABLISHMENT EXPENSES		
2557		Ground Rent, Heating, Lighting, Insurance and Repairs		2730 11 7
		„ ADMINISTRATIVE AND OFFICE EXPENSES		
9637		Salaries and National Insurance	10505 16 5	
1380		Pension and Pensions Premiums	1563 14 11	
1935		Printing and Stationery	1753 13 6	
1369		Postages and Telephones	1508 8 4	
694		Office Furniture and Equipment	366 3 8	
400		Travelling Expenses	342 13 8	
554	15969	Other Charges	871 10 1	16912 0 7
		„ JOURNAL AND PUBLICATIONS		
2688		Salaries and Pensions Premiums	3266 14 7	
19900		Printing	19559 8 0	
2254		Postages and Envelopes	2463 5 4	
1108	25950	Sundry	1535 15 5	26825 3 4
		„ TECHNICAL COMMITTEES		
5317		Salaries and Pensions Premiums	6951 2 9	
3061	8378	Printing and Other Charges	3338 0 0	10289 2 9
		„ GARDEN PARTY		
	2897	Expenses		2071 2 0
	568	„ EXAMINATIONS EXPENSES		682 17 3
	540	„ MEETINGS		945 3 10
	1930	„ ANGLO-AMERICAN AERONAUTICAL CONFERENCES RESERVE		1500 0 0
	444	„ DINNERS AND RECEPTIONS		358 13 8
		„ LIBRARY		
1682		Salaries and Pensions Premiums	1765 8 5	
271	1953	Expenses	379 3 7	2144 12 0
	490	„ BRANCH EXPENSES		540 0 0
	145	„ PRIZES AND DONATIONS		170 3 3
	383	„ CHARTER SCHOLARSHIPS		400 0 0
	203	„ LEGAL AND PROFESSIONAL CHARGES		409 18 0
	—	„ SECRETARY'S VISITS TO THE DOMINIONS		1447 19 7
	—	„ PAYMENT TO CANADIAN AERONAUTICAL INSTITUTE		365 3 3
	233 (Commemorative Dinner) 500 (Film)			
	3678	„ BALANCE BEING SURPLUS OF INCOME OVER EXPENDITURE FOR YEAR CARRIED TO BALANCE SHEET		1330 12 11
	£66818			£69123 4 0

FOR THE YEAR ENDED 31st DECEMBER 1954

1953 Figures £			£ s. d.	£ s. d.
23892		By Annual Subscriptions		25311 14 7
11264		„ Donations and Grants		11038 2 8
135		„ Interest on Investments (Gross)	226 7 8	
107		„ Income Tax Recovered, 1953/1954	51 13 3	
5084	5326	„ Surplus on Endowment Fund Income and Expenditure Account for Year	5090 5 0	5368 5 11
—		„ Profit on Sale of Investment		126 12 5
		„ Journal and Publications		
15497		Advertising Revenue	15207 2 5	
6581	22078	Sales	7654 2 8	22861 5 1
		„ Technical Committees		
1797		Sales		2290 4 9
		„ Garden Party		
1717		Sale of Tickets	1247 0 0	
126	1843	Profit on Programme	251 9 1	1498 9 1
618		„ Examinations Fees		628 9 6
£66818				£69123 4 0

AERONAUTICAL

BALANCE SHEET

1953 Figures £		£ s. d.	£ s. d.	£ s. d.
	SHARE CAPITAL—			
	Authorised—40 Shares of 1s. each		2 0 0	
1	*Issued*—21 Shares of 1s. each fully paid			1 1 0
	ROYAL AERONAUTICAL SOCIETY ENDOWMENT FUND—			
	Capital Account—(Subject to depreciation of Investments)			
132774	Balance at 31st December 1953		133490 8 1	
711	*Add*—Entrance Fees received during year		835 16 0	
—	Profit on sale of Investments		42 15 7	
5			134368 19 8	
(Donation)				
133490				
	Income Account—			
9104	Balance as at 31st December 1953		9103 14 6	143472 14 2
142594				
	PILCHER MEMORIAL FUND—			
	Capital Account—			
100	As at 31st December 1953		99 14 0	
	Income Account—			
85	Balance at 31st December 1953	80 1 4		
	Less—Excess of Expenditure over Income for			
5	year to date	5 2 8	74 18 8	174 12 8
180				
	USBORNE MEMORIAL FUND—			
	Capital Account—			
109	As at 31st December 1953		109 2 5	
	Income Account—			
94	Balance at 31st December 1953	89 15 0		
	Less—Excess of Expenditure over Income for			
4	year to date	4 10 8	85 4 4	194 6 9
199				
	HERBERT AKROYD STUART FUND—			
	Capital Account—			
691	As at 31st December 1953		691 9 0	
	Income Account—			
615	Balance at 31st December 1953	632 14 3		
18	*Add*—Income for year to date	44 8 8	677 2 11	1368 11 11
(Surplus)				
1324				
	R.38 MEMORIAL FUND—			
	Capital Account—			
981	As at 31st December 1953		981 13 10	
	Income Account—			
1046	Balance at 31st December 1953	1106 16 6		
61	*Add*—Income for year to date	68 14 10	1175 11 4	2157 5 2
2088				
146386	*Forward*			147368 11 8

TRUSTS LIMITED

31st DECEMBER 1954

1953 Figures £		£ s. d.	£ s. d.	£ s. d.
1	CASH IN HAND			1 1 0
	ROYAL AERONAUTICAL SOCIETY ENDOWMENT FUND—			
	Leasehold Property at cost *less* amounts written off 4, 8, and 9, Hamilton Place			
14185	At cost	14185 1 9		
7781	*Less*—Amortisation written off to date ...	8436 1 9	5749 0 0	
6404				
	Furniture at cost *less* depreciation			
6173	At cost	6396 1 11		
3264	*Less*—Depreciation written off to date ...	3584 1 11	2812 0 0	
2909				
132066	Investments at cost		131075 11 3	
	Market Value 31st December 1954: £126,544 (1953: £117,537)			
141379			139636 11 3	
	Current Assets—			
750	Sundry Debtors	375 0 0		
1784	Cash at Bank	3515 4 11	3890 4 11	
143913			143526 16 2	
1319	*Less*—Amount due to the Royal Aeronautical Society		54 2 0	143472 14 2
142594				
	PILCHER MEMORIAL FUND—			
156	Investment at cost		156 5 0	
	Market Value 31st December 1954: £134 (1953: £131)			
24	Cash at Bank		18 7 8	174 12 8
180				
	USBORNE MEMORIAL FUND—			
175	Investment at cost		174 11 1	
	Market Value 31st December 1954: £149 (1953: £145)			
24	Cash at Bank		19 15 8	194 6 9
199				
	HERBERT AKROYD STUART FUND—			
1278	Investments at cost		1278 11 1	
	Market Value 31st December 1954: £1,127 (1953: £1,092)			
46	Cash at Bank		90 0 10	1368 11 11
1324				
	R.38 MEMORIAL FUND—			
2005	Investments at cost		2004 18 9	
	Market Value 31st December 1954: £1,741 (1953: £1,688)			
83	Cash at Bank		152 6 5	2157 5 2
2088				
146386	*Forward*			147368 11 8

AERONAUTICAL

BALANCE SHEET

1953 Figures		£ s. d.	£ s. d.	£ s. d.
£				
146386	*Forward*			147368 11 8
	EDWARD BUSK MEMORIAL FUND—			
	Capital Account—			
449	As at 31st December 1953		449 6 1	
	Income Account—			
239	Balance at 31st December 1953	242 15 7		
4	*Add*—Surplus of Income over Expenditure for year to date	3 10 4	246 5 11	695 12 0
692				
	EDWARD BUSK STUDENTSHIP IN AERONAUTICS—			
	Capital Account—			
5418	Balance at 31st December 1953		5418 10 4	
1	*Add*—Premium received on conversion of Defence Bonds		2 0 0	
5419			5420 10 4	
	Income Account—			
103	Balance at 31st December 1953	147 8 6		
44	*Add*—Surplus of Income over Expenditure for year to date	56 8 6	203 17 0	5624 7 4
5566				
	WILBUR WRIGHT MEMORIAL FUND—			
	Capital Account—			
2137	As at 31st December 1953		2136 17 11	
	Income Account—			
231	Balance at 31st December 1953	202 9 6		
29	*Less*—Excess of Expenditure over Income for year to date	19 1 8	183 7 10	2320 5 9
2339				
	SIMMS GOLD MEDAL FUND—			
	Capital Account—			
528	As at 31st December 1953		527 15 9	
	Income Account—			
83	Balance at 31st December 1953	92 16 9		
10	*Add*—Surplus of Income over Expenditure for year to date	13 13 3	106 10 0	634 5 9
621				
	ALSTON MEMORIAL FUND—			
	Capital Account—			
245	Balance at 31st December 1953		245 6 0	
	Add—Profit on sale of Investments		5 2 10	
			250 8 10	
	Income Account—			
81	Balance at 31st December 1953	80 5 3		
1 (Excess)	*Add*—Surplus of Income over Expenditure for year to date	3 16 4	84 1 7	334 10 5
325				
155929	*Forward*			156977 12 11

TRUSTS LIMITED—*Continued*

31st DECEMBER 1954

1953 Figures £		£ s. d.	£ s. d.	£ s. d.
146386	*Forward*			147368 11 8
	EDWARD BUSK MEMORIAL FUND—			
658	Investments at cost		658 8 8	
	Market Value 31st December 1954: £648 (1953: £628)			
34	Cash at Bank		37 3 4	695 12 0
692				
	EDWARD BUSK STUDENTSHIP IN AERONAUTICS—			
	Investments at valuation 31st December 1951		4806 10 0	
	Investments at cost		601 6 6	
5408			5407 16 6	
	Market Value 31st December 1954: £5,759 (1953: £5,615)			
158	Cash at Bank		216 10 10	5624 7 4
5566				
	WILBUR WRIGHT MEMORIAL FUND—			
2251	Investments at cost		2250 14 9	
	Market Value 31st December 1954: £2,272 (1953: £2,184)			
88	Cash at Bank		69 11 0	2320 5 9
2339				
	SIMMS GOLD MEDAL FUND—			
585	Investments at cost		585 0 0	
	Market Value 31st December 1954: £537 (1953: £517)			
36	Cash at Bank		49 5 9	634 5 9
621				
	ALSTON MEMORIAL FUND—			
290	Investment at cost		295 2 10	
	Market Value 31st December 1954: £278 (1953: £290)			
35	Cash at Bank		39 7 7	334 10 5
325				
155929	*Forward*			156977 12 11

AERONAUTICAL

BALANCE SHEET

1953 Figures		£ s. d.	£ s. d.	£ s. d.
£				
155929	*Forward*			156977 12 11
	GEOFFREY DE HAVILLAND MEMORIAL FUND—			
	Capital Account—			
4176	As at 31st December 1953		4175 17 5	
	Income Account—			
327	Balance at 31st December 1953	329 14 10		
	Add—Surplus of Income over Expenditure for			
3	year to date	11 1 10	340 16 8	4516 14 1
4506				
£160435				£161494 7 0

REPORT OF THE AUDITORS TO THE

In our opinion and to the best of our information and according to the expenditure account give a true and fair view of the state of the Company's affairs of the Funds for the year ended on that date.

We have obtained all the information and explanations which to the the company has kept proper books of account and the above mentioned accounts, required by the Companies Act, 1948.

3 Frederick's Place, Old Jewry, London, E.C.2.

22nd March 1955.

TRUSTS LIMITED—*Continued*

31st DECEMBER 1954

1953 Figures £		£ s. d.	£ s. d.	£ s. d.
155929	*Forward*			156977 12 11
	GEOFFREY DE HAVILLAND MEMORIAL FUND—			
4427	Investments at cost		4426 10 0	
	Market Value 31st December 1954: £4,072 (1953: £3,879)			
79	Cash at Bank		90 4 1	4516 14 1
4506				
£160435				£161494 7 0

MEMBERS OF AERONAUTICAL TRUSTS LIMITED

explanations given to us the above balance sheet and the annexed income and and of the Funds administered by it as at 31st December 1954 and of the surplus

best of our knowledge and belief were necessary for our audit. In our opinion which are in agreement therewith, give in the prescribed manner the information

(*Signed*) PRICE WATERHOUSE & CO.

AERONAUTICAL

INCOME AND EXPENDITURE ACCOUNTS

ROYAL AERONAUTICAL SOCIETY

1953 Figures			
£		£	s. d.
655	To Amortisation of Leasehold Property	655	0 0
309	„ Depreciation of Furniture	319	11 5
8	„ Legal Expenses	8	8 0
5084	„ Surplus of Income over Expenditure for year transferred to Royal Aeronautical Society	5090	5 0
£6056		£6073	4 5

PILCHER

£		£	s. d.
10	To 1954 Award	10	10 0
£10		£10	10 0

USBORNE

£		£	s. d.
10	To 1954 Award	10	10 0
£10		£10	10 0

HERBERT AKROYD

£		£	s. d.
—	To Income for year carried to Balance Sheet	44	8 8
21 (Award)			
18 (Surplus)			
£39		£44	8 8

R.38

£		£	s. d.
61	To Income for year carried to Balance Sheet	68	14 10
£61		£68	14 10

EDWARD BUSK

£		£	s. d.
21	To 1954 Award	21	0 0
3	„ Surplus of Income over Expenditure for year carried to Balance Sheet	3	10 4
£24		£24	10 4

TRUSTS LIMITED

FOR THE YEAR ENDED 31st DECEMBER 1954

ENDOWMENT FUND

1953 Figures £		£ s. d.
2642	By Interest on Investments (Gross)	2642 1 4
1054	„ Interest on Investments (*less* tax)	1096 4 8
860	„ Refund of Income Tax	834 18 5
1500	„ Rents Receivable	1500 0 0
£6056		£6073 4 5

MEMORIAL FUND

£		£ s. d.
5	By Interest on Investments (Gross)	5 7 4
5	„ Excess of Expenditure over Income for year carried to Balance Sheet	5 2 8
£10		£10 10 0

MEMORIAL FUND

£		£ s. d.
6	By Interest on Investments (Gross)	5 19 4
4	„ Excess of Expenditure over Income for year carried to Balance Sheet	4 10 8
£10		£10 10 0

STUART FUND

£		£ s. d.
38	By Interest on Investments (Gross)	37 11 10
1	„ Interest on Investments (*less* tax)	4 1 10
—	„ Refund of Income Tax	2 15 0
£39		£44 8 8

MEMORIAL FUND

£		£ s. d.
59	By Interest on Investments (Gross)	58 19 2
2	„ Interest on Investments (*less* tax)	5 17 0
—	„ Refund of Income Tax	3 18 8
£61		£68 14 10

MEMORIAL FUND

£		£ s. d.
24	By Interest on Investments (Gross)	24 10 4
£24		£24 10 4

AERONAUTICAL

INCOME AND EXPENDITURE ACCOUNTS

EDWARD BUSK STUDENTSHIP

		£ s. d
£		
165	To 1954 Award	165 0 0
44	„ Surplus of Income over Expenditure for year carried to Balance Sheet	56 8 6
£209		£221 8 6

WILBUR WRIGHT

1953 Figures		
£		£ s. d.
100	To 1954 Award	100 0 0
£100		£100 0 0

SIMMS GOLD

		£ s. d.
£		
7	To 1954 Award	5 16 8.
10	„ Surplus of Income over Expenditure for year carried to Balance Sheet	13 13 3
£17		£19 9 11

ALSTON

		£ s. d.
£		
10	To 1954 Award	10 0 0
—	„ Surplus of Income over Expenditure for year carried to Balance Sheet	3 16 4
£10		£13 16 4

GEOFFREY DE HAVILLAND

		£ s. d.
£		
120	To 1954 Award	120 0 0
3	„ Surplus of Income over Expenditure for year carried to Balance Sheet	11 1 10
£123		£131 1 10

TRUSTS LIMITED—*Continued*

FOR THE YEAR ENDED 31st DECEMBER 1954

IN AERONAUTICS

£		£ s. d.
134	By Interest on Investments (Gross)	135 2 8
38	,, Interest on Investments (*less* tax)	48 7 8
37	,, Refund of Income Tax	37 18 2
£209		£221 8 6

MEMORIAL FUND

1953 Figures

£		£ s. d.
59	By Interest on Investments (Gross)	37 5 8
12	,, Interest on Investments (*less* tax)	24 0 0
—	,, Refund of Income Tax	19 12 8
29	,, Excess of Expenditure over Income for year carried to Balance Sheet	19 1 8
£100		£100 0 0

MEDAL FUND

£		£ s. d.
16	By Interest on Investments (Gross)	16 7 4
1	,, Interest on Investments (*less* tax)	1 17 6
—	,, Refund of Income Tax	1 5 1
£17		£19 9 11

MEMORIAL FUND

£		£ s. d.
9	By Interest on Investments (Gross)	13 16 4
1		
(Excess)		
£10		£13 16 4

MEMORIAL FUND

£		£ s. d.
121	By Interest on Investments (Gross)	121 6 2
2	,, Interest on Investments (*less* tax)	5 17 0
—	,, Refund of Income Tax	3 18 8
£123		£131 1 10

Canadian Aeronautical Institute

The Canadian Aeronautical Institute held its first Annual Meeting on 25th May 1954, and since then there has been a steady increase in membership; it now totals almost one thousand. During the year the Institute began to take its place in International Aviation, for in Montreal the Canadian Aeronautical Institute and the Institute of the Aeronautical Sciences have held a Joint Conference.

At the first Annual Meeting the Society was represented by Mr. B. S. Shenstone, a Member of Council, and the Secretary. The Institute was presented with the Annual Reports of the Society for 1867-1893, with the good wishes of the Society and the hopes for the future success of the Institute. It would appear that these hopes are being fulfilled, for the Institute is in process of adding to the number of its Branches.

American Visit

As detailed in the Journal of January 1955, Captain J. L. Pritchard is making a Lecture Tour in America. He has been speaking of The Society and the Wright Brothers, and other subjects.

At the time of writing no full account can be given of his tour, but it is apparent, from the letters already received by the Secretary, that he is having large and appreciative audiences, and that at each stop the "British Colony" is showing its pleasure at his advent.

With him he has taken "Powered Flight—the Story of the Century," and his audiences have been enthralled by this historical film made by the Shell Film Unit.

Staff

Both Miss Barwood and Miss Voyce have been on the Staff for more than twenty-five years. To commemorate these years of continued service the President, Sir Sydney Camm, on behalf of the Members, presented to each a gift, significant of the appreciative esteem in which they are both held. Miss Barwood in the General Office, and Miss Voyce in the Accounts Department, have given to the Society the work of both heart and brain and that without stint. Then the President wished them well; now the good wishes are reiterated by the Council.

Associate Fellowship Examination

During the year Part I of the Examination in the New Syllabus has been introduced. In May the total entry at home and abroad was 79, and in December the number of candidates was increased to 92.

The examinations have been held in the following countries: Australia, Burma, Canada, Holland, India, Israel, New Zealand, and Northern Ireland.

This has only been possible by the kindly assistance of individuals, Universities, and other Institutions, and the Council acknowledge this help, and record their gratitude.

It would appear that the New Syllabus is creating considerable interest; it has been welcomed by many teaching establishments.

The Secretary of the Society

The Council wish to record their appreciation of the work of Dr. Ballantyne as Secretary of the Society and the President particularly adds his personal tribute to the great help given him. The Secretary has not spared himself in pursuing the Society's interests as witness his many visits to the various Branches all over the country.

Obituaries

The Council regret to record the death of the following Members of the Society:

F. B. Adler (*Graduate*) (Australian Division)
Squadron Ldr. R. Alexander (*Associate Fellow*)
E. S. Barwick (*Student*) (Australian Division)
J. Bell (*Associate*)
I. K. Bennett (*Associate Fellow*)
Professor S. Brodetsky (*Fellow*)
A. W. S. Clarke (*Associate Fellow*)
H. A. Collins (*Associate*)
R. J. Goodman Crouch (*Fellow*)
T. W. Delury (*Associate*)
Dr. G. P. Douglas (*Fellow*)
Dr. J. Dubsky (*Companion*)
A. M. Duxbury (*Student*)
Wing Cdr. D. M. Egan (*Associate Fellow*)
Wing Cdr. L. P. Gibson (*Associate Fellow*)
W. W. Greenfield (*Fellow*)
Air Chief Marshal Sir Roderic Hill (*Fellow*)
Sub-Lt. (A) M. A. Hutchison, R.N.V.R. (*Graduate*)
Mrs. Patricia Hyde-Edwards (*Associate*)
Wing Cdr. A. N. Jarvis (*Associate*)
V. P. Kelly (*Associate Fellow*)
G. Lindsay-Murray (*Associate*)
W. G. Montgomery (*Associate*)
B. S. Murphy (*Associate*)
G. T. Perkins (*Associate*)
C. H. Powell (*Associate Fellow*)
F. P. Raynham (*Fellow*)
Major A. A. Ross (*Fellow*)
Flight Lt. R. J. Ross (*Associate Fellow*)
Flight Lt. R. J. Saker (*Student*)
L. F. G. Simmons (*Fellow*)
Captain P. W. Smith (*Fellow*)
Major C. J. Stewart (*Fellow*)
Lt. (E) J. H. Stock, R.N. (*Student*)
Major General The Rt. Hon. Sir Frederick Sykes (*Honorary Fellow*)
W. R. Turnbull (*Fellow*)
W. A. Watts (*Associate Fellow*)
R. W. Webster (*Associate Fellow*)
B. Wilkinson (*Associate Fellow*)
Flying Officer C. J. W. Woodruff (*Student*)
J. H. Wright (*Associate*)
Flying Officer J. S. Wright (*Student*)
O. Wright (*Associate*)

TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

A Combination of the Quasi-Cylinder and Slender Body Theories

By

C. H. E. WARREN (*Royal Aircraft Establishment*)

and

L. E. FRAENKEL (*Imperial College*)

THE QUASI-CYLINDER and slender body theories for the supersonic flow past bodies of revolution[1, 2, 3] have been much used in recent years because, for reasonably simple body profiles, these theories permit a simple and rapid calculation of the first-order pressure distributions and aerodynamic forces. It is assumed in both theories that the body profile slope is small; in the quasi-cylinder theory it is also assumed that the body radius is nearly constant, whereas in the slender body theory it is assumed that the thickness ratio of the body (maximum diameter/length) is small.

In the present note these two theories are combined completely. From a strictly mathematical point of view nothing is gained by this combination, and, furthermore, application of the combined theory to a particular case is in general a little more laborious than application of either of the original theories. However, the combined theory does offer two practical advantages: firstly it appears to give better general agreement with exact results than either of the constituent theories, and secondly it removes the need to decide which of the two theories is more suitable to the problem at hand (this decision is often a difficult one in practice).

We are indebted to Professor G. N. Ward for a remark which made clear to us the possibility of a combined theory*.

NOTATION

a_i	values of x at points of discontinuity
$B=(M^2-1)^{\frac{1}{2}}$	where M is free stream Mach number
C_p	pressure coefficient
D	drag force
K_0, K_1	modified Bessel functions of the second kind
l	body length
p	Heaviside operator with respect to x
$R(x)$	body radius
$\overline{R}$	mean radius of quasi-cylinder
$S(x)$	body cross-sectional area $\pi R^2(x)$
$\mathscr{U}$	free stream velocity
U, U_1, V, V_1	special functions defined in Section 1
(x, r, θ)	cylindrical polar co-ordinates
α	angle of incidence
$\Delta S_i' = S'(a_i+) - S'(a_i-)$	
$\eta(x)$	profile slope of quasi-cylinder
ρ	free stream density
Φ, ϕ	*see* equation (1)
Suffix $_0$	denotes value at zero incidence
Suffix $_1$	denotes effect of incidence
$\bar{\ }$	denotes Heaviside operational form

Received 25th November 1954.

*Since this paper was written the authors' attention has been drawn to the fact that results similar to those given here have also been obtained by Professor M. J. Lighthill, and are published in the Princeton University Press series, *High Speed Aerodynamics and Jet Propulsion*, in Volume 6, entitled "General Theory of High Speed Aerodynamics," Section E, Article 7.

1. SPECIAL FUNCTIONS

The quasi-cylinder theory involves certain special functions which we define in terms of their Heaviside operational forms. Asymptotic expansions are also quoted to indicate the general behaviour of these functions, all of which vanish for $x<0$.

$$\frac{K_0(p)}{pK_1(p)} \rightleftharpoons U_1(x) \sim x - \frac{x^2}{4} + \ldots . \qquad (x \ll 1)$$

$$\sim \log 2x + \frac{1}{2x^2}(1 - 2\log 2x) + \ldots . \qquad (x \gg 1)$$

$$-\frac{K_1(p)}{pK_1'(p)} \rightleftharpoons V_1(x) \sim x - \frac{x^2}{4} + \ldots . \qquad (x \ll 1)$$

$$\sim 1 + \frac{1}{x^2} + \ldots . \qquad (x \gg 1)$$

The derivatives of these functions, $U_1'(x)=U(x)$ and $V_1'(x)=V(x)$, are also of importance. U, U_1, V, V_1, and two other functions of the U family which are useful in calculating pressure distributions at zero incidence, are tabulated in Refs. 2, 3 and 4.

2. THE COMBINED PERTURBATION POTENTIAL

Cylindrical polar co-ordinates (x, r, θ) are taken such that the x-axis is the body axis and such that the undisturbed stream has components $\mathscr{U}\cos\alpha$ and $\mathscr{U}\sin\alpha$ parallel and perpendicular to this axis. The body extends from $x=0$ to $x=l$, the body radius $R(x)$ being continuous in the range $0<x<l$. The functions $R'(x)$, $R''(x)$, defining the profile slope and its derivative, may be discontinous at $x=a_i\,(i=0, 1, \ldots, n;\ a_0=0;\ a_n=l)$. $R(x)$ and its derivatives are taken to vanish for

$x<0$. There is no restriction on the length of the intervals $(a_i - a_{i-1})$. The complete velocity potential is

$$\Phi = \mathscr{V}(x\cos\alpha + r\cos\theta\sin\alpha + \phi). \quad . \quad (1)$$

The quasi-cylinder solution for the perturbation potential is, in operational form[2],

$$\underline{\phi}(p, r, \theta) = -\frac{K_0(Bpr)}{BpK_1(Bp\bar{R})}\underline{\eta}(p) - \alpha\cos\theta\frac{K_1(Bpr)}{BpK_1'(Bp\bar{R})}, \quad . \quad . \quad . \quad . \quad (2)$$

where $\bar{R}$ and $\eta(x)$ denote the mean radius and slope of the quasi-cylindrical profile. On the body this becomes

$$\underline{\phi} = -\bar{R}\frac{K_0(Bp\bar{R})}{Bp\bar{R}K_1(Bp\bar{R})}\underline{\eta}(p) - \alpha\cos\theta\bar{R}\frac{K_1(Bp\bar{R})}{Bp\bar{R}K_1'(Bp\bar{R})}$$

i.e.

$$\phi(x, \bar{R}, \theta) = -\bar{R}\int_{\xi=0-}^{x} U_1\left(\frac{x-\xi}{B\bar{R}}\right)d\eta(\xi) + \alpha\cos\theta\bar{R}V_1\left(\frac{x}{B\bar{R}}\right), \quad . \quad . \quad . \quad (3)$$

where the integral, which results from the product theorem for a discontinuous function, is a Stieltjes integral.

The "simple" slender body solution[5], which retains only the dominant terms in the K_0 and K_1 of the general operational solution (*i.e.* which assumes $r/(x-a_i)$ small), becomes in the present case

$$\phi(x, r, \theta) = -\frac{1}{2\pi}\int_{\xi=0-}^{x}\log\frac{2(x-\xi)}{Br}dS'(\xi) + \alpha\cos\theta\frac{R^2(x)}{r} \quad . \quad . \quad . \quad . \quad (4)$$

In view of the asymptotic expansions (for large values of their argument) of U_1 and V_1, and because $S' \simeq 2\pi\bar{R}\eta$, $S \simeq S(0+)$ for a quasi-cylinder, both the forms (3) and (4) are approximately contained in

$$\phi(x, r, \theta) = -\frac{1}{2\pi}\int_{\xi=0-}^{x} U_1\left(\frac{x-\xi}{Br}\right)dS'(\xi) + \frac{\alpha\cos\theta}{\pi r}\int_{\xi=0-}^{x} V_1\left(\frac{x-\xi}{Br}\right)dS(\xi) \quad . \quad (5)$$

On the surface of quasi-cylinders (5) is as accurate as (3); on and near slender bodies, with $x - a_i \gg r$, (5) is as accurate as (4); and in the regions where (4) fails because $r/(x-a_i)$ is not small, (5) remains valid *on the body*, because these regions are short and therefore quasi-cylindrical. Equation (5) may also be justified rigorously on the basis of order arguments similar to those in Ref. 3.

With suitable approximations the pressure on the body given by equation (5) reduces to the forms given in Ref. 3 (*see* equation (6*b*) which follows). The advantages of the present formulation are that the analysis is clarified by the expression for the combined velocity potential; that localised errors at discontinuities in $S''(x)$ are avoided*; and that the results are equally valid for quasi-cylinders and slender bodies.

*These errors can also be avoided by shifts of the origin in equation (23) of Ref. 3, but they do occur if this equation is used as it stands.

The perturbation velocity $\partial\phi/\partial x$ is given by†

$$\frac{\partial\phi}{\partial x} = -\frac{1}{2\pi Br}\int_{\xi=0-}^{x} U\left(\frac{x-\xi}{Br}\right)dS'(\xi) + \frac{\alpha\cos\theta}{\pi Br^2}\int_{\xi=0-}^{x} V\left(\frac{x-\xi}{Br}\right)dS(\xi) \quad . \quad . \quad (6a)$$

The discontinuity terms are extracted from these integrals, and the generalised rule for integration by parts, based on the Stieltjes integral, is applied to the remainder to obtain

$$\frac{\partial\phi}{\partial x} = -\frac{1}{2\pi Br}\sum_{i=0}^{n}\Delta S_i' U\left(\frac{x-a_i}{Br}\right) - \frac{1}{2\pi}\int_{\xi=0-}^{x} U_1\left(\frac{x-\xi}{Br}\right)dS''(\xi) + \frac{\alpha\cos\theta}{\pi}\left\{\frac{S(0+)}{Br^2}V\left(\frac{x}{Br}\right) + \frac{1}{r}\int_{\xi=0-}^{x} V_1\left(\frac{x-\xi}{Br}\right)dS'(\xi)\right\} \quad . \quad . \quad . \quad . \quad (6b)$$

3. THE PRESSURE COEFFICIENT

The pressure coefficient is

$$C_p = 1 - \left(\frac{\nabla\Phi}{\mathscr{V}}\right)^2 + O\left[\left(\frac{\partial\phi}{\partial x}\right)^2\right].$$

If the "thickness" and "incidence" parts of the perturbation potential respectively are denoted by ϕ_0 and ϕ_1, corresponding to the two terms in (5), we have on the body, using the boundary condition for $\partial\phi/\partial r$,

$$C_p = C_{p0} + C_{p1},$$

where

$$\left.\begin{aligned} C_{p0} &= -2\frac{\partial\phi_0}{\partial x} - R'^2 \\ \text{and } C_{p1} &= -\frac{2\partial\phi_1}{\partial x} + \alpha^2\cos^2\theta + \frac{2\alpha\sin\theta}{R}\frac{\partial\phi_1}{\partial\theta} - \frac{1}{R^2}\left(\frac{\partial\phi_1}{\partial\theta}\right)^2 \end{aligned}\right\} \quad (7)$$

It seems doubtful, however, that the combined theory will offer any substantial improvement for the incidence problem: in the remainder of this note our attention is confined to the problem at zero incidence.

4. THE DRAG AT ZERO INCIDENCE

In an actual application the drag, as predicted by the combined theory, is probably best calculated by a direct numerical integration of the pressure distribution. However the drag formula of the combined theory can be derived very rapidly and may have a certain academic interest. The drag at zero incidence is

$$\frac{D_0}{\frac{1}{2}\rho\mathscr{V}^2} = -\int_0^1\left(2\frac{\partial\phi_0}{\partial x} + R'^2\right)S'(x)\,dx$$

†Strictly, since in certain cases (5) is valid on the surface only, the partial derivative $\partial\phi/\partial x$ cannot always be formed but only the total derivative $d\phi/dx$. However, in these cases (6*a*) does contain the dominant terms of the true $\partial\phi/\partial x$, which are initially $O(R')$. Where $\partial\phi/\partial x$ is $O(RR'\log R)$, (5) is valid off the body and (6*a*) is certainly correct. It can in fact be shown by somewhat lengthy order arguments that (6*a*) provides everywhere as good an approximation as is attainable with linearised theory.

Now $\dfrac{\partial \phi_0}{\partial x}(x, R) = \dfrac{d}{dx}\phi_0(x, R) - \dfrac{\partial \phi_0}{\partial r}\dfrac{dR}{dx} = \dfrac{d}{dx}\phi_0 - R'^2$

Hence $$\frac{D_0}{\frac{1}{2}\rho \mathscr{U}^2} = 2\int_{x=0-}^{l+} \phi_0(x, R)\, dS'(x) + \int_0^l R'^2(x)\, S'(x)\, dx,$$

$$= -\frac{1}{\pi}\int_{x=0-}^{l+} dS'(x) \int_x^{\xi=0-} U_1\left(\frac{x-\xi}{BR(x)}\right) dS'(\xi) + \int_0^l R'^2(x)\, S'(x)\, dx, \quad . \quad . \quad (8a)$$

$$= -\frac{1}{2\pi}\int_{x=0-}^{l+}\int_{\xi=0-}^{l+} \left[U_1\left(\frac{x-\xi}{BR(x)}\right) + U_1\left(\frac{\xi-x}{BR(\xi)}\right)\right] dS'(x)\, dS'(\xi) + \int_0^l R'^2(x)\, S'(x)\, dx. \quad . \quad . \quad . \quad (8b)$$

This expression contains the drag formulae of Refs. 1, 2 and 3 as particular cases. For a true quasi-cylinder the second term is negligible, and the substitution $R(x) \simeq \overline{R}$ reduces the double integral to an alternative form of Lighthill's result[1, 2] for the drag of quasi-cylinders. For truly slender bodies having their discontinuities spaced well apart $U_1(x) \simeq \log 2x$ is substituted (for $a_i - a_{i-1} \gg R_{\max}$) and the points $x = \xi = a_i$ are excluded from the area of integration (this may conveniently be done by using (8*a*) and writing the upper limit of the inner integral as $\xi = x-$); Lighthill's result[3] for the drag of slender bodies is then recovered.

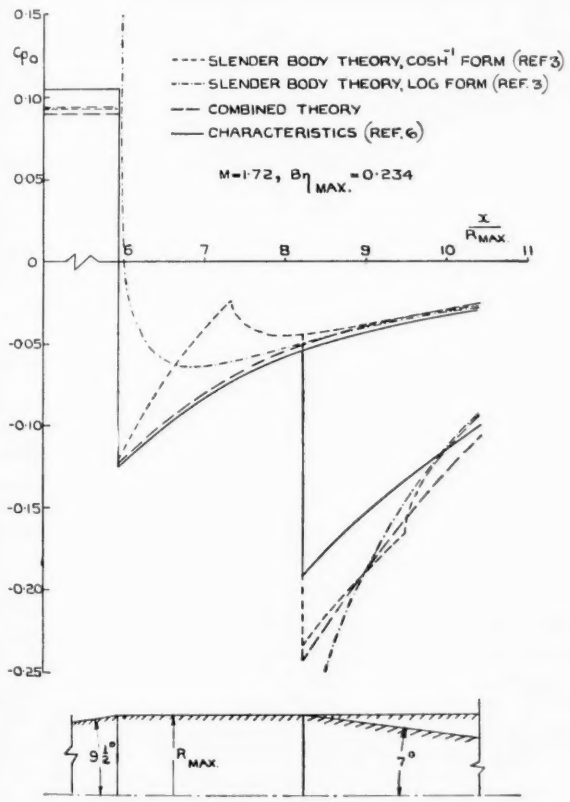

FIGURE 1. Pressure distribution on a cone-cylinder with conical afterbody.

6. APPLICATIONS

Pressure distributions at zero incidence, as predicted by various theories, are compared in Figs. 1 and 2. The slender body values are not those corresponding to equation (4) above, but are those given by Ref. 3; the "$\cosh^{-1}$ form" corresponds to equation (23) of Ref. 3, while the "log form" uses the substitution of equation (29). The quasi-cylinder results in Fig. 2 are based on a mean radius

$$\overline{R} = \tfrac{1}{2}[R(0) + R(0{\cdot}65l)].$$

The combined-theory and quasi-cylinder pressure distributions were readily evaluated by means of the tabulated functions of Ref. 4, no numerical integration being necessary.

Figures 1 and 2 show that, while the combined theory is just as good, but no better than the two constituent theories in general, it is superior to these two theories in certain cases. Fig. 1 shows that downstream of a discontinuity in $S'(x)$ the combined theory predicts

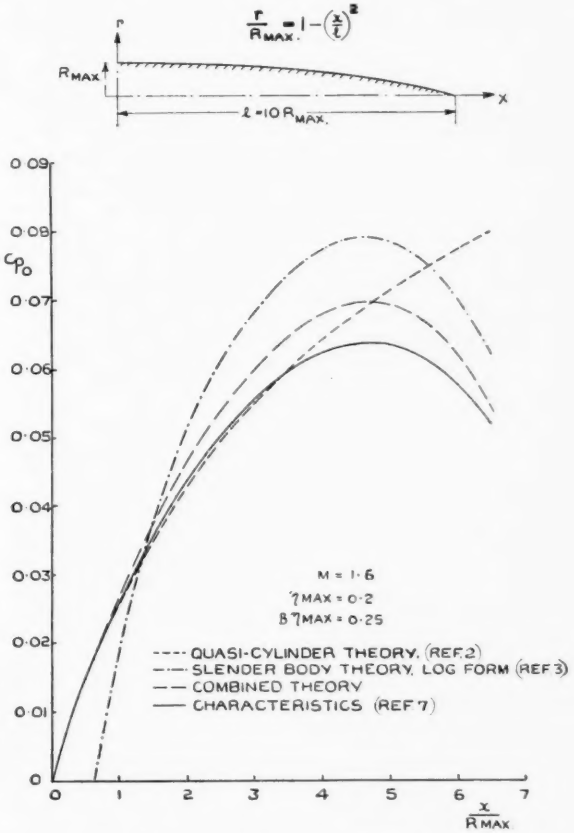

FIGURE 2. Pressure distribution on an afterbody of parabolic profile.

both qualitatively and quantitatively the trend given by the exact theory, in contradistinction to the log form of the slender body theory which yields an infinite pressure immediately downstream of the discontinuity, and the $\cosh^{-1}$ form which yields a kink in the pressure distribution curve at the wrong place. Fig. 2 shows that the combined theory predicts the trend given by the exact theory for an afterbody, in contradistinction to the quasi-cylinder theory, which fails to predict the recompression.

Strictly the condition for the applicability of the combined theory is $|B\eta_{\max}| \ll 1$, where $\eta_{\max}$ is the numerical maximum value of the profile slope, but this theory is seen to give reasonable values when $|B\eta_{\max}|$ is as large as 0·25. This gain in accuracy may possibly justify the somewhat greater amount of labour required in application of the combined theory; the computations are still substantially shorter than those required for most other theories.

ACKNOWLEDGMENT

The senior author is indebted to the Chief Scientist, Ministry of Supply, for permission to publish this note.

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A Note on the Vibration of Systems Containing Epicyclic Gears

By

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THE PURPOSE of this note is to present a table of the receptances of simple epicyclic gears and to show how they may be used. This table of results has two main uses. In the first place the receptances simplify the calculation of the natural frequencies of torsional systems containing these gears by the methods explained previously[1]. Secondly, responses of systems (which incorporate these gears) to given harmonic excitations may be estimated, either in the absence of damping, or when there is damping present of known amount in the component sub-systems. This second use of receptances is illustrated by a simple example in this note; it is based upon the fact that the receptances of a compound system may be built up from those of its sub-systems irrespective of whether there is damping present or not. The equations which are used for this purpose (*see* Ref. 1, Table II) are the same in each case, the only difference being that the various receptances are complex when there is damping present[2] and are all real when the system is conservative.

The receptances of the epicyclic gears are only useful when the frequencies of oscillation that are considered, and the running speed, are fairly low. This is because, at higher frequencies and speeds, distortion within an epicyclic gear—particularly of the flexible annulus ring—modifies the natural frequencies and the response to harmonic excitation. Limitations of this sort are, of course, inherent in the vibration analysis of *any* idealised system; but it is likely that this restriction is a severe one for certain types of epicyclic gears.

As this note is concerned, in part, with *complex* receptances, it is convenient to use the familiar complex representation of harmonic motions (*see*, for instance, Ref. (2)). The notation is that used previously[1] with the following additions:—

F	amplitude of applied torque
I	polar moment of inertia
M	mass
N	number of planet gears
r	radius
x	angular displacement

The symbols I, M, r and x carry subscripts which refer to the various parts of an epicyclic gear. These are:

a	annulus
c	cage
p	planets
s	sun

These subscripts are also carried by the various receptance functions. That is to say, α_{sc} for a planetary gear represents the angular harmonic displacement of the sun wheel when a harmonic torque of unit amplitude is applied to the cage.

Certain relations exist between the radii r_a, r_p and r_s of the pitch circles and r_c, the radius of the circle containing the planet spindles. Thus,

$$\left.\begin{aligned} r_s + r_p &= r_c \\ r_s + 2r_p &= r_a \end{aligned}\right\} \quad . \quad . \quad . \quad (1)$$

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The symbol I_p denotes the polar moment of inertia of a single planet about its own axis. The symbol I_c represents not only the polar moment of inertia of the cage and planet spindles about the central axis but also includes a term (equal to $NM_pr_c^2$) to allow for the translation of the planets.

Three types of epicyclic gear are dealt with. They are

(*a*) Star Gear (cage fixed)
(*b*) Planetary Gear (annulus fixed)
(*c*) Solar Gear (sun fixed).

The detailed derivation is given of the receptances of the second of these types. Extensions of the theory to more complicated types of epicyclic gears (*e.g. see* Ref. 3) may be made using the methods that are outlined below.

1. THE RECEPTANCES OF A PLANETARY GEAR

The kinetic energy of a planetary gear is given by

$$T=\tfrac{1}{2}\left[I_s\dot{x}_s^2+NI_p\dot{x}_p^2+I_c\dot{x}_c^2\right] \quad . \quad (2)$$

Now the angular displacements x_s and x_p are given in terms of x_c by the relations[3]

$$x_s=\frac{2r_c}{r_s}x_c \quad ; \quad x_p=\frac{r_c}{r_p}x_c. \quad . \quad . \quad (3)$$

The kinetic energy may therefore be expressed in the alternative forms

$$T=\frac{1}{2}\left[I_s+NI_p\left(\frac{r_s}{2r_p}\right)^2+I_c\left(\frac{r_s}{2r_c}\right)^2\right]\dot{x}_s^2 \quad . \quad (4)$$

$$T=\frac{1}{2}\left[I_s\left(\frac{2r_c}{r_s}\right)^2+NI_p\left(\frac{r_c}{r_p}\right)^2+I_c\right]\dot{x}_c^2 \quad . \quad (5)$$

Suppose that a torque $F_se^{i\omega t}$ acts at the sun wheel.

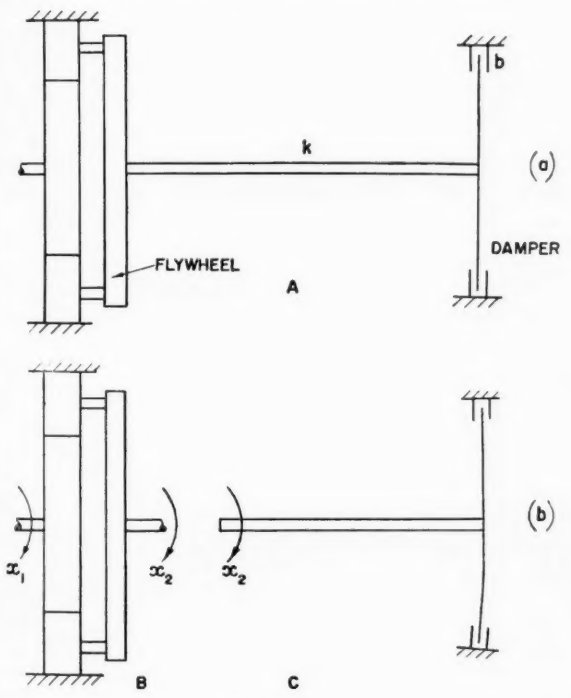

FIGURE 1.

TABLE I

RECEPTANCES OF EPICYCLIC GEARS

Star gear	$\alpha_{ss}=\frac{1}{\Delta}$	$\alpha_{aa}=\frac{(r_s/r_a)^2}{\Delta}$	$\alpha_{sa}=\alpha_{as}=\frac{-(r_s/r_a)}{\Delta}$
	$\Delta=-\omega^2\left[I_s+NI_p\left(\frac{r_s}{r_p}\right)^2+I_a\left(\frac{r_s}{r_a}\right)^2\right]$		
Planetary gear	$\alpha_{ss}=\frac{1}{\Delta}$	$\alpha_{cc}=\frac{(r_s/2r_c)^2}{\Delta}$	$\alpha_{sc}=\alpha_{cs}=\frac{(r_s/2r_c)}{\Delta}$
	$\Delta=-\omega^2\left[I_s+NI_p\left(\frac{r_s}{2r_p}\right)^2+I_c\left(\frac{r_s}{2r_c}\right)^2\right]$		
Solar gear	$\alpha_{cc}=\frac{1}{\Delta}$	$\alpha_{aa}=\frac{(2r_c/r_a)^2}{\Delta}$	$\alpha_{ca}=\alpha_{ac}=\frac{(2r_c/r_a)}{\Delta}$
	$\Delta=-\omega^2\left[I_c+NI_p\left(\frac{r_c}{r_p}\right)^2+I_a\left(\frac{2r_c}{r_a}\right)^2\right]$		

Symbols: I = polar moment of inertia; N = no. planets; r = radius.
Subscripts: a = annulus; c = cage; p = planet; s = sun.
Note: (1) r_a, r_p, r_s = pitch circle radii; r_c = radius of circle containing planet axes. (2) I_p refers to single planet and its own axis. (3) I_c includes cage, planet spindles and allowance ($=NM_pr_c^2$) for translation of planets (where M_p = mass of planet).

By means of Lagrange's equations it is found from (4) that

$$\left[I_s+NI_p\left(\frac{r_s}{2r_p}\right)^2+I_c\left(\frac{r_s}{2r_c}\right)^2\right]\ddot{x}_s=F_se^{i\omega t}.$$

By seeking a solution in which x_s is proportional to $e^{i\omega t}$ it is found that

$$x_s=\frac{-1}{\omega^2\left[I_s+NI_p\left(\frac{r_s}{2r_p}\right)^2+I_c\left(\frac{r_s}{2r_c}\right)^2\right]}F_se^{i\omega t}=\alpha_{ss}F_se^{i\omega t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The variation of x_c is now found by the use of the first of equations (3); that is,

$$x_c=\frac{-(r_s/2r_c)}{\omega^2\left[I_s+NI_p\left(\frac{r_s}{2r_p}\right)^2+I_c\left(\frac{r_s}{2r_c}\right)^2\right]}F_se^{i\omega t}=\alpha_{cs}F_se^{i\omega t} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The receptances α_{ss} and α_{cs} are given in Table I.

In a similar manner, the motion caused by a harmonic torque $F_ce^{i\omega t}$ may be found from equation (5). Thus the receptances α_{sc} and α_{cc} may be derived.

2. EXAMPLE

Figure 1(*a*) shows a light shaft with an epicyclic gear at one end, and a light viscous damping device at the other. There are six planets carried on spindles attached to a flywheel. The constants relating to the system are as follows:—

	Mass (lb.)	*Radius of gyration (in.)*	*No. of teeth*
Sun wheel	4	2	48
Each planet	1	1	24
Flywheel, including spindles	10	3	—

The diametral pitch is 9, the shaft stiffness is $k=3\times10^4$ lb. in. per radian and the damper constant is $b=3\times10^2$ lb. in. per radian per second.

It is required to determine as a function of ω, the amplitude of the sun wheel motion if the sun wheel is subjected to a harmonic torque of amplitude F_s lb. in. and frequency ω radians per second*.

The system A, with receptances α, may be broken down into sub-systems B and C, with receptances β and γ, as in Fig. 1(*b*). If the co-ordinates shown are used, then it may be shown (*see* Table II of Ref. 1) that

$$\alpha_{11}=\beta_{11}-\frac{\beta_{12}^2}{\beta_{22}+\gamma_{22}} \quad . \quad . \quad . \quad (8)$$

The values of the receptances β and γ can now be calculated as follows:

The radii are

$$r_s=\frac{48}{18}=\frac{8}{3}\text{ in.};\quad r_p=\frac{4}{3}\text{ in.};\quad r_c=4\text{ in.}$$

and the moments of inertia are

$$\left.\begin{aligned} I_s&=\frac{4\times2^2}{384}=\frac{16}{384}\text{ lb. in. sec.}^2;\quad I_p=\frac{1}{384}\text{ lb. in. sec.}^2\\ I_c&=\frac{10\times3^2}{384}+\frac{6\times1\times4^2}{384}=\frac{186}{384}\text{ lb. in. sec.}^2 \end{aligned}\right\}$$

These values give the required receptances β which may be found in Table I. They are

$$\left.\begin{aligned} \beta_{11}&=\frac{-384}{\omega^2[16+6+186(1/3^2)]}=-\frac{9}{\omega^2}\text{ rad./(in. lb.)}\\ \beta_{22}&=-\frac{1}{\omega^2}\text{ rad./(in. lb.)};\quad \beta_{12}=-\frac{3}{\omega^2}\text{ rad./(in. lb.)} \end{aligned}\right\}$$

In order to calculate the receptance γ_{22} which is required in equation (8), it is convenient to start from the equations of motion of system C of Fig. 1(*b*). If x_3 denotes the angular displacement of the damper, then a couple $F_2e^{i\omega t}$ applied at the severed end of the shaft causes motion that is given by

$$\left.\begin{aligned} k(x_2-x_3)&=F_2e^{i\omega t}\\ k(x_2-x_3)&=b\dot{x}_3 \end{aligned}\right\}$$

Camb. Mech. Sci. Tripos, Pt. II, 1954.

If solutions for x_2 and x_3 are now sought in which the displacements vary as $e^{i\omega t}$, x_2 is found to be

$$x_2=\left[\frac{1}{k}+\frac{1}{ib\omega}\right]F_2e^{i\omega t}=\gamma_{22}F_2e^{i\omega t} \quad . \quad (9)$$

The numerical value of γ_{22} is therefore

$$\gamma_{22}=\frac{1}{3\times10^4}-\frac{i}{3\times10^2\omega}\text{ rad./(in. lb.)}$$

The receptance α_{11} may now be found from equation (8); it is

$$\alpha_{11}=-\frac{9}{\omega^2}-\frac{9/\omega^4}{\left[-\frac{1}{\omega^2}+\frac{1}{3\times10^4}-\frac{i}{3\times10^2\omega}\right]}\text{ rad./(in. lb.)}$$

If now the notation $y=\omega\times10^{-2}$ is adopted, this reduces to

$$\alpha_{11}=-\frac{9}{\omega^2}\left\{\frac{y^2-iy}{(y^2-3)-iy}\right\}.$$

From this it is found that

$$|\alpha_{11}|=\frac{9}{\omega^2}\left(\frac{y^4+y^2}{(y^2-3)^2+y^2}\right)^{\frac{1}{2}}=\frac{9}{\omega}\left(\frac{\omega^2+10^4}{\omega^4-5\times10^4\omega^2+9\times10^8}\right)^{\frac{1}{2}}$$
rad./(in. lb.)

so that the required amplitude is

$$F_s|\alpha_{11}|=\frac{9F_s}{\omega}\left(\frac{\omega^2+10^4}{\omega^4-5\times10^4\omega^2+9\times10^8}\right)^{\frac{1}{2}}\text{ radians} \quad . \quad . \quad . \quad . \quad (10)$$

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Reviews

N.A.S.C. TITANIUM SYMPOSIUM. *held in October 1954 at Cleveland, Ohio. National Aircraft Standards Committee, Aircraft Industries Association. Washington 5, D.C. 419 pp. Illustrated. 4 dollars.*

There is doubt as to whether John Cabot or Amerigo Vespucci first discovered America. There can, however, be but little doubt as to what the natives were discovered to be doing. They were holding a symposium and, in spite of many subsequent civilising influences, they have never been broken of this habit. This note deals with weighty evidence of the continued persistence of this ineffective method of disseminating knowledge.

In October 1954, a two day meeting, sponsored by the over-elaborately named National Aircraft Standards Committee, Aircraft Industries Association, was held in a hotel at Cleveland, Ohio. Here one hopes and imagines from the remarkable jocularity of the published discussion, a good time was had by all.

Before an audience of about two hundred and fifty, some twenty-three papers were read and discussed with marked informality. The record shows the participants in many cases to have been on Christian name, leg-pulling terms, and in a mood when not so very wise-cracks seemed like wise ones, until perpetuated in print. The minutes of the Puddle-cum-Dyke Parish Council on a wet evening would be at least as objective and far less suggestive of the performance of cross-talk comedians.

So much for generalities with regard to this publication of four hundred and nineteen pages weighing over two and a half pounds. At the present time airframe engineers accept fire-walls and jet-pipe shrouds as suitable fields for the use of commercially pure titanium sheet. They are, however, in some doubt as to other applications of the metal. A discussion, however wandering and discursive, on the employment of titanium alloys as a direct substitute for alloy steel bolts, nuts, shear pins, rivets, and so on, would therefore be expected to excite interest, for there would appear to be a possibility of reducing the weight of these parts by as much as 40 per cent.

Most of the papers deal with titanium alloy fasteners from a particular view point. A group, none up to Royal Aeronautical Society standards, sets out the views of aircraft engineers who have had experience of these fasteners. There are wide differences of opinion. Some taking part in these somewhat strange proceedings are satisfied that, technically, all alloy steel airframe fasteners can be satisfactorily replaced by titanium alloy ones. Others, and the writer is among their number, consider that the defects of titanium alloy bolts, because of their doubtful fatigue properties and thread pick-up troubles, are not yet sufficiently satisfactory to be used at all. Further, many, even among those who believe titanium alloys can be employed in the applications now under consideration, are in a complete state of confusion as to the cost of weight saved. Different authorities, apparently speaking with equal confidence or recklessness, give figures as wide apart as $400 and less than $40 per pound. Others seem to regard $100 as a realistic figure.

This badly edited, unindexed account of a badly organised and badly controlled discussion on titanium alloy fasteners can be purchased for thirty shillings. The aeronautical engineer in search of facts should save his money. If, on the other hand, he requires fancies and even whimsies, then he does get something for the price. The metallurgist, due to a considerable number of macro-photos and of photo-micrographs, will be less inclined to feel that he has purchased a gold brick.—P.L.T.

MOTEURS, HÉLICES, RÉACTEURS (PISTON ENGINES, PROPELLERS, TURBO-JETS). *(In French.) J. Soissons, Dunod, Paris, 1954. 111 pp. 44 diagrams. 1,000 fr.*

This little volume is based on lectures given at the French test pilots' school, and so it is intended for those with some professional acquaintance with the problems of aircraft propulsion, albeit of a primarily practical nature. Even so, it appears to the reviewer to be somewhat haphazard in its selection and arrangement of material.

An introductory chapter reviews the elementary theory relating to propulsive efficiency, the power required in flight, and basic thermodynamics. The only comment required here is that the *p-V* diagram (Fig. 1) on p. 4 carries the label " power " where " pressure " is intended, and that the symbol ε is used on p. 4 as compression (*i.e.* volume) ratio, but on p. 12 as pressure ratio.

The first major section deals with piston engines. The practical working cycles are contrasted with their ideal counterparts (English speaking readers will be intrigued to know that B.M.E.P. stands for " Brake Main Efficiency Pressure "!), and then the influence of the various parameters on the engine performance is discussed. One feels that this section would be more easily assimilated if the Charge Weight Law were used as the basis for discussion. Then follows a review of the major auxiliary components —fuel, oil and cooling systems, instruments, propellers and their governors. While this ably summarises the requirements and current practice, it suffers greatly from the complete lack of diagrams: a purely verbal description of various carburettor systems is of little use unless one is already *au fait* with the subject, in which case such instruction is superfluous. On p. 41 arises another linguistic misunderstanding where the term " boost " is interpreted as a unit of manifold pressure, one boost being defined as equal to one pound per square inch, relative to standard pressure.

The second section deals in similar fashion with the turbo-jet. The discussion of performance is sound, emphasising as it does the influence of maximum turbine temperature and of combustion stability limits on the attainable thrust at altitude. The various components are then reviewed, as are the fuel and control systems, with special reference to the Nene and Atar. Diagrams of the fuel systems of these engines are provided, but on such a reduced scale as to be almost illegible. The implication that axial compressors are usually designed so that the absolute gas velocities are all wholly axial is misleading, to say the least.

The final section deals with the general requirements for flight testing of various types of engine, and the volume closes with Appendices on piston engine handling (" before take-off—ensure that the fuel, oil and coolant tanks have been filled " and so forth) and on the properties of fuels and oils.

To summarise, it means that the author is not clear whether he is writing a textbook on thermodynamics and performance, an engine servicing manual or a set of pilot's notes, with the result that the overall impression is scrappy.

While the book might usefully supplement the lecture course from which it is derived, one doubts whether it could have much application when used alone.—J. R. PALMER.

ROCKET EXPLORATION OF THE UPPER ATMOSPHERE. *Edited by R. L. F. Boyd and M. J. Seaton in consultation with H. S. W. Massey, F.R.S. Pergamon Press Ltd., 1954. 376 pp. Illustrated. 75s.*

This book is a special supplement to the "Journal of Atmospheric and Terrestrial Physics" and the papers included in it were read at the Conference arranged by the Upper Atmosphere Rocket Research Panel of the United States and by the Gassiot Committee of the Royal Society of London. It is thus a report of the first major international conference on the exploration of the upper atmosphere and almost all who have contributed to modern knowledge on this subject have written papers. It is undoubtedly the most important volume so far produced on upper atmosphere research. The considerable work done in America, both with V.2s and other test vehicles, is included and the reader is given full information both of the techniques used and the results obtained.

The book falls into seven main groups. Firstly, there is the review of the rocket techniques used. Secondly, work to determine pressure, temperature and winds at altitude by rocket and by other available methods. The third group of papers deals with the composition of the atmosphere, particular attention being given to work on the ozone layer. The fourth group is devoted to work on the ionosphere and covers solar radiation and geomagnetic variations as well. Only one paper is included in the next group, on cosmic ray measurement by rocket, although a considerable amount of work has been done by use of rockets to investigate cosmic ray intensity at various heights; this work has been published elsewhere. The last two groups deal with laboratory studies and theoretical considerations of suggested experiments.

The papers are well documented and form an encyclopedia of published knowledge. The book is essential to everyone interested in the subject.—D.C.S.

AIRCRAFT OF THE 1914-18 WAR. *Edited by D. A. Russell. Compiled by C. G. Thetford and E. J. Riding. Second Edition. Harleyford Publications, Marlow, 1954. 234 pp. 80 plans. 234 photographs. 42s.*

It is this reviewer's misfortune that he frequently gets inquiries for particulars of abstruse aircraft. He has a "panel of experts" who help him when he is finally frustrated and many times he is referred to "Thetford and Riding" which has not, hitherto, been in his particular collection. It is with some joy, therefore, that he is in a position to review a reissue of this very useful book.

Photographs, line drawings, and descriptive matter are supplied of Allied and German machines, but before accepting all the particulars as gospel it is as well to read the last paragraph of the preface. The layout and reproduction are excellent, but at the price one is entitled to expect this.

To the specialist in the period there will be details open to criticism but the seeker after a quick reference will find it most useful.

For those who have been combing the secondhand market for years this reissue will be a godsend.—F.H.S.

TABLE OF THE GAMMA FUNCTION FOR COMPLEX ARGUMENTS. *National Bureau of Standards, Applied Mathematics Series 34. Government Printing Office, Washington 25, D.C., 1954. 105 pp. $2.00.*

The range, interval of the arguments, and number of decimal places in these tables have been chosen so as to be of particular convenience to the user. The tables give the real and imaginary parts of $\log_e \Gamma(z)$ for $z=x+iy$, $x=0(\cdot1)10$, $y=0(\cdot1)10$ each to 12 decimals. A comprehensive introduction contains a discussion of the important properties of the gamma function with methods for extending the range of the table. A detailed discussion of direct and inverse interpolation is presented with special attention to the accuracy which can be achieved through the use of the suggested methods. Auxiliary tables of $\sin \pi x$, $\cos \pi x$, $\sinh \pi x$ and $\cosh \pi x$ are given to 15 decimal places or 15 significant figures for $x=0(\cdot1)10$ to facilitate extension of the scope of the table.

Additions to the Library

A.C.S.I.L. Library. BIBLIOGRAPHY OF PUBLISHED REFERENCES TO SERVOMECHANISMS AND ASSOCIATED DEVICES. Admiralty. 1955.

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Hodge, J. GAS TURBINE SERIES. VOL. I. CYCLES AND PERFORMANCE ESTIMATION. Butterworth. 1955.

Ladenburg, R. W., B. Lewis, R. N. Pease and H. S. Taylor (*Editors*). HIGH SPEED AERODYNAMICS AND JET PROPULSION. VOL. IX. PHYSICAL MEASUREMENTS IN GAS DYNAMICS AND COMBUSTION. O.U.P. 1955.

Oberth, H. MENSCHEN IM WELTRAUM: NEUE PROJEKTE FUR RAKETEN- UND RAUMFAHRT. Econ-Verlag: Dusseldorf. 1954.

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Schiller, L. STROMUNG DURCH ROHRE. UMSTROMUNG VON KORPERN BEI ZWEIDIMENSIONALER STROMUNG. UMSTROMUNG VON KORPERN BEI RAUMLICHER STROMUNG. Springer. 1955.

Sears, W. R. (*Editor*). HIGH SPEED AERODYNAMICS AND JET PROPULSION. VOL. VI. GENERAL THEORY OF HIGH SPEED AERODYNAMICS. O.U.P. 1955.

Ward, G. N. LINEARIZED THEORY OF STEADY HIGH-SPEED FLOW. C.U.P. 1955.

Reports

AERODYNAMICS

Boundary Layer

Average skin-friction drag coefficients from tank tests of a parabolic body of revolution (N.A.C.A. R.M.-10). E. J. Mottard and J. D. Loposer. N.A.C.A. Report 1161 (1954).

Average skin-friction drag coefficients were obtained from boundary layer total-pressure measurements on a parabolic body of revolution (N.A.C.A. R.M.-10, basic fineness ratio 15) in water at Reynolds numbers from $4{\cdot}4 \times 10^6$ to 70×10^6. The tests were made in the Langley tank No. 1 with the body sting-mounted at a depth of two maximum body diameters.—(1.1.3.1).

Compressible Flow

See also Wings and Aerofoils

The calculation of the wave drag of a family of low-drag axi-symmetric nose shapes of fineness ratio 4·5 at zero incidence at supersonic speeds. G. B. Marson. CoA Note 10 (*May* 1954).

The pressure drag coefficients of a particular family of convex logarithmic projectile nose shapes in which the nose angle is an important parameter have been calculated over a range of supersonic Mach numbers using a rapid approximate method due to Zienkiewicz. The optimum nose angle for minimum wave drag of these profiles for each Mach number has been obtained.—(1.2.3).

On transonic flow past a wave-shaped wall. C. Kaplan. N.A.C.A. Report 1149 (1953).

The simplified non-linear differential equation for transonic flow past a wavy wall is solved by the method of integration in series. A general procedure for the solution of the resulting recurrence formulae is shown and illustrated by a number of examples. A numerical test of convergence is applied to a key power series in k, the transonic similarity parameter.—(1.2.2.1).

A comparison of the experimental subsonic pressure distributions about several bodies of revolution with pressure distributions computed by means of the linearized theory. C. W. Matthews. N.A.C.A. Report 1155 (1953).

A comparison is made of the theoretical and experimental subsonic compressible pressure coefficient distributions about several bodies of revolution. Two equations are presented for approximately determining the subsonic compressible pressure coefficient distributions from the incompressible pressure coefficient distributions.—(1.2.1.1).

Control Surfaces

The effect of compressibility on elevator flutter. D. E. Williams. A.R.C., C.P. No. 185 (*March* 1953).

The effect of compressibility on elevator flutter is investigated by using two-dimensional control surface derivatives for Mach numbers of 0 and 0·7. It is shown that compressibility may have a considerable effect when the stick is fixed, but that the effect is small when the stick is free.—(1.3.2).

Aerodynamic forces and loadings on symmetrical circular-arc airfoils with plain leading-edge and plain trailing-edge flaps. J. F. Cahill et al. N.A.C.A. Report 1146 (1953).

A two-dimensional wind-tunnel investigation has been made of 6- and 10-per cent. thick symmetrical circular arc aerofoil sections equipped with 0·15-chord plain leading-edge flaps and 0·20-chord plain trailing-edge flaps. The tests consisted of measurements of the aerodynamic forces and surface pressures at low Mach numbers (about 0·15) and several Reynolds numbers ($0{\cdot}7 \times 10^6$ to 18×10^6 based on the aerofoil chord). A generalised method is developed that permits the determination of the chordwise pressure distribution over sharp-edge aerofoils with plain leading- and trailing-edge flaps of arbitrary size and deflection.—(1.3.4 × 1.10.2.2).

Internal Flow

A wind-tunnel investigation of entry loss on propeller turbine installations. Parts I and II. J. Seddon and A. Spence. R. & M. 2894 (*August* 1948, *published* 1954).

Part I describes wind-tunnel tests on (*a*) a series of models of annular entries, with and without propeller, in the 5-ft. tunnel; (*b*) a set of large circular blade roots on a full-size nacelle in the 24-ft. tunnel. From a generalised analysis of the results empirical rules are suggested for the estimation of spinner loss, duct loss, and blade-root loss, making up the total entry loss in flight. Part II describes wind-tunnel tests on models of a number of alternative ducted spinners for a typical engine, and for comparison, one annular entry similar to those tested in Part I. A detailed analysis of the loss is given, using methods evolved in Part I.—(1.5.1 × 27).

Shocks in helical flows through annular cascades of stator blades. R. Wasserman and A. W. Goldstein. N.A.C.A., T.N. 3329 (*December* 1954).

A method is presented for calculating supersonic potential flows in annular cascades of blades by the method of characteristics. A flow and several cascade designs were computed.—(1.5).

Stability and Control

The influence of rolling moments on spin recovery as observed in model-spinning tests. D. J. Harper. R. & M. 2831 (*April* 1950, *published* 1954).

Several aspects of model-spinning test technique have been brought into prominence by recent full-scale developments. Correlation between model and full-scale recoveries has been poor in some cases, and it appears from model tests of some new aircraft that full-scale recovery may depend on other means in addition to the normal use of rudder and elevator. —(1.8.3.1).

Operating characteristics of an acceleration restrictor as determined by means of a simulator. A. Assadourian. N.A.C.A., T.N. 3319 (*December* 1954).

The operating characteristics of an acceleration restrictor were determined from tests on a simulator consisting of a control stick geared to a magnetic brake unit and an analog computor. The restrictor worked on the principle of stopping the elevator motion by means of a brake when a signal which was a function of normal acceleration, pitching acceleration, and pitching velocity reached a certain preset value. The results obtained with three brake-operating signals are presented.—(1.8.2 × 33.1.2).

Analytical determination of the mechanism of an airplane spin recovery with different applied yawing moments by use of rotary-balance data. S. M. Burk. N.A.C.A., T.N. 3321 (*December* 1954).

An analysis of an aeroplane recovery from a right spin is made where constant applied anti-spin yawing moments due to application of 800 and 1,600 pounds of force at the left wing tip are considered. Use is made of rotary-balance data and a step-by-step integration process of Euler's equations of motion allowing six degrees of freedom.—(1.8.3).

Wings and Aerofoils

See also Control Surfaces and Testing and Instruments

Theoretical supersonic drag of non-lifting infinite-span wings swept behind the Mach lines. T. Nonweiler. R. & M. 2795 (*October* 1950, *published* 1954).

The drag of a non-lifting swept wing of infinite span is investigated for supersonic flow when the Mach lines from the wing apex lie ahead of the wing leading edge. The wing section is assumed to be arbitrary but identical over the entire wing-span. The drag is found according to the linear equations of supersonic flow by considering the flow due to a system of superposed source planes.—(1.10.1.1 × 1.2.3).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

Pressure plotting and balance measurements in the high speed wind tunnel on a half-model of a 90-deg-apex delta wing with fuselage. A. C. S. Pindar and J. R. Collingbourne. R. & M. 2844 (*September* 1949, *published* 1954).

Tests were made at a Reynolds number of $1{\cdot}8\times10^6$ and Mach numbers up to 0·93. The wing tip was cropped to a taper of 1/7 and the wing section was R.A.E. 102, symmetrical, 10 per cent. thickness/chord at 35 per cent. chord.—(1.10.2.2).

Experiments in the compressed air tunnel on swept-back wings including two delta wings. R. Jones, C. J. W. Miles and P. S. Pusey. R. & M. 2871 (*March* 1948, *published* 1954).

The investigation was undertaken to provide data relating to C_L, C_D and C_m at high values of Reynolds number on wings of triangular plan form.—(1.10.2.2).

Wing flow tests at subsonic and transonic speeds on four thin, low aspect ratio, swept-back wings. A. D. Wood and D. H. Henshaw. N.A.E., LR-118 (*November* 1954).

The wings were so chosen that three values of aspect ratio and two values of thickness/chord ratio were represented. Sweepback angles of 60° and 53° at the leading edge and 0° and 18° at the trailing edge were selected. The aerofoil sections chosen were N.A.C.A. 0003-63 and N.A.C.A. 0005-63. The tests were carried out at Mach numbers between 0·6 and 1·2. Reynolds numbers, based on the mean aerodynamic chord, varied between $0{\cdot}5\times10^6$ and $1{\cdot}3\times10^6$. A comparison is made between lift, pitching moment and drag due to lift characteristics.—(1.10.2.2).

*The solution of the generalized Prandtl equation for swept wings. J. H. De Leeuw, W. Eckhaus and A. I. van de Vooren. N.L.L. Report F.*156 (*September* 1954).

A general method is given for the solution of the generalised Prandtl equation for swept wings. The method is applied to two particular wings and the results are compared with results according to Multhopp's and Weissinger's theories.—(1.10.1.2).

Helicopter Aerodynamics

An analysis of N.A.C.A. helicopter reports. R. N. Liptrot. A.R.C., C.P. No. 183 (*January* 1954).

Theory is compared with flight and model tests, in order to obtain empiric correcting factors which will enable reliable performance estimates to be made for new helicopter designs. A survey of general theory is followed by an analysis of certain American reports. Correcting factors for effective blade drag for tip speed ratio, compressibility and stalling of the retreating blade are derived. A method of calculating the retreating blade tip angle of attack for twisted blades is presented.—(1.11).

Testing and Instruments

Approximate wall corrections for an oscillating swept wing in a wind tunnel of closed circular section. W. E. A. Acum and H. C. Garner. A.R.C., C.P. No. 184 (*January* 1954).

The oscillatory interference upwash for a circular tunnel is derived from the corresponding steady upwash. Corrections to measured derivatives of a slowly pitching wing are calculated by Multhopp's lifting surface theory. A satisfactory approximate method using interference parameters for a small wing is given, and an extension to rectangular tunnels is suggested.—(1.12.1.1).

The determination of the pressure distribution over an aerofoil surface by means of an electrical potential analyser. S. C. Redshaw. R. & M. 2915 (*December* 1952, *published* 1954).

The potential flow, both with and without circulation, around several thin aeroplane wings has been studied by means of a three-dimensional potential analyser. It is shown that, by using the normal assumptions made in the exercise of the linear perturbation theory, it is possible to obtain the pressure distribution for small angles of incidence, as well as the slope of the lift-incidence curve, easily and rapidly. Experiments were made to remove the effect of boundary restraint in a manner analogous to that used in a flexible-walled wind tunnel. Suggestions are made for producing a potential analyser of increased scope together with the possibility of extending the work to curved and twisted thin wings.—(1.12.6 × 1.10.1.1).

Die praktische Anwendbarkeit der Wasseranalogie in quantitativer Form auf spezielle Probleme der Gasdynamik. H. Bomelburg. Max-Planck-Institut fur Stromungsforschung. No. 10 (1954).—(1.12 × 1,2,3).

DESIGN AND CONSTRUCTION

Design considerations for wings having minimum drag due to lift. W. A. Tucker. N.A.C.A., T.N. 3317 (*December* 1954).

The problem of increasing the range of supersonic aircraft by the use of twisted and cambered wings is considered, primarily for the purpose of developing a rational method for the selection of a design lift coefficient. Relations and curves are presented from which a suitable selection may be made, depending on the relative importance of maximum range and top speed.—(4.2.2.5).

MATHEMATICS

Formulas para el calculo de funciones analiticas cuyas partes real e imaginaria se dan sobre arcos alternados de una circunferencia. G. Moretti. Comunicaciones e informes. C-9 (*July* 1954).

Poisson's integral allows the determination of the real part of an analytic function knowing its imaginary part along a circumference. Formulae are presented to solve an analogous but somewhat more complicated problem: to determine the unknown parts of an analytic function knowing its real part along some arc of circumference and its imaginary part along the others. The problem is completely solved in two symmetrical cases.—(22).

*On the asymptotic solution of wave propagation and oscillation problems. A. P. Burger. N.L.L. Report F.*157 (*November* 1954).

Boundary value problems with the wave equation for harmonic time dependence are transformed, by a one-sided Laplace transform, into hyperbolic problems with one more dimension. Using asymptotic properties of the transform, the solution can be found in the form of an asymptotic series. The method is applied to a pair of two-dimensional problems which are mathematically largely equivalent, namely diffraction by a plane screen with slit, and the oscillating aerofoil at high frequencies (or in near-sonic flow).—(22).

MECHANICAL ENGINEERING

The critical whirling speeds and natural vibrations of a shaft carrying a symmetrical rotor. E. Downham. R. & M. 2854 (*December* 1950, *published* 1954).

Part of a programme of model experiments designed to establish an accurate method for calculating the critical whirling speeds of complex systems is described. The critical whirling speeds and natural vibrations of a single shaft flexibly supported and carrying a flexible rotor of appreciable moment of inertia have been investigated and good agreement has been obtained between experimental and calculated results for the rotating system. Some discrepancy between calculated and experimental results for the vibration of the non-rotating system is thought to be due to the operational characteristics of the flexible bearing.—(23.7).

STRUCTURES

Loads

See also Aerodynamics, Stability and Control.

Gust experience of a helicopter and an airplane in formation flight. A. D. Crim. N.A.C.A., T.N. 3354 (*December* 1954).

A single-rotor helicopter and an aeroplane have been flown in formation in rough air for the purpose of measuring and comparing their responses to gusts. Rough-air flights were also made by the helicopter alone at several different air speeds over the same ground path.—(33.1.1 × 3.9).

Theory and Analysis

Load diffusion in plastic structures. L. M. Tucker and R. B. Twiss. A.R.C., C.P. 186 (*December* 1952).

Theoretical and experimental investigations have been made of the inherent advantages, in plastic structures, of resin bonded shear joints over comparable pin joints, and the most efficient material distribution for load diffusion.—(33.2.4.13.0).